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Lessons learned from oil pipeline natech accidents and recommendations for natech scenario development

Final Report

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Abstract

Natural hazards can impact oil transmission pipelines with potentially adverse consequences on the population and the environment. They can also cause significant economic impacts to pipeline operators. Currently, there is only limited historical information available on the dynamics of natural hazard impact on pipelines and Action A6 of the EPCIP 2012 Programme aimed at shedding light on this issue. This report presents the findings of the second year of the study that focused on the analysis of onshore hazardous liquid transmission pipeline natechs, with special emphasis on natural hazard impact and damage modes, incident consequences, and lessons learned for scenario building. Due to the limited amount of data available on European pipeline natech incidents, the study was supplemented with information from U.S. pipeline natech incidents.

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Executive Summary

Natural hazards can impact oil transmission pipelines with potentially adverse consequences on the population and the environment. They can also cause significant economic impacts to pipeline operators. Currently, there is only limited historical information available on the dynamics of natural hazard impact on pipelines and Action A6 of the EPCIP 2012 Programme aimed at shedding light on this issue.

For this purpose this study focused on the collection and analysis of hazardous liquid and natural gas transmission pipeline incident data. During the study, European and U.S. incident data sources were reviewed, relevant data was collected, and imported into a specifically developed database-driven incident data analysis system. The analysis system and preliminary results of the incident data analysis were reported in the first year final report of the study. This report presents the findings of the second year of the study that focused on onshore hazardous liquid transmission pipeline natechs, with special emphasis on natural hazard impact and damage modes, incident consequences, and lessons learned for scenario building.

Due to the low number of incidents, the European incident data alone was not sufficient to identify natural-hazard specific impact and failure modes at the oil pipeline components and to develop representative natech scenarios. For this reason, data on U.S. pipeline natech incidents was included in this study. Although the dominating natural hazards vary due to geological and climatic differences, the additional use of U.S. data allowed a more complete analysis, the results of which are equally applicable to the European oil pipeline network for selected natural hazards.

The analysis of the data available for Europe showed that natechs constitute 4% of all reported oil and petroleum product pipeline incidents in Europe in the last 40 years (1971-2012). The total number of identified natechs is 20. Recent natechs are rare and there is only one pipeline natech incident since 1995. 90% of the natechs involve the pipe body, whereas the remainder involves pump stations. There are no reported natechs at intermediate storage facilities.

Geological hazards were the primary trigger (65%), followed by hydrological (20%) and climatic hazards (10%). Meteorological hazards played a minor role. The main incident initiators among geological hazards were landslides and the rest was mostly subsidence events primarily affecting elements other than the pipe body. No earthquake related natech was reported. All hydrological incidents were related to floods and no other water-related hazards such as stream scouring was observed. Although cold weather conditions are common in Europe, only hot weather related climatic natechs were reported that were relatively minor compared to other natechs.

The total amount of crude oil and petroleum products released due to natech incidents was 6,000 m^3, 40% of which was subsequently recovered. The median release volume was 120 m^3 and at least half of the released amount was recovered in 75% of the incidents. The total estimated cost of the natech incidents at oil and petroleum product pipelines in Europe as corrected for inflation is about 40 million Euro. The highest cost for a single event is 14.4 million Euro while the median cost is 0.8 million Euro.

The analysis of the U.S. Department of Transportation hazardous liquid transmission pipeline incident data for a period of 25 years (1986-2012) showed that there were 387 natechs corresponding to about 5.5% of all pipeline incidents. The vulnerability of pipeline network components varies

significantly with natural hazard and system types. Unlike in Europe, meteorological hazards were the main trigger, resulting in the highest number of incidents (40%) and the highest total cost (60%). Geological and climatic hazards were other major hazards with about 20% contribution each. However, climatic natechs resulted in less than 10% of the total release and the corresponding total cost was even more insignificant (2%). While hydrological hazard triggered incidents occurred less frequently, their consequences were significant and correspond to one third of the total release and overall cost.

The analysis also showed that the susceptibility to natural hazards is not uniform among the different hazardous liquid pipeline network parts (e.g. pipe run, pumping/metering stations, and intermediate tank farms/terminals). All incidents related to hydrological hazards involved the main pipeline body; the same holds for incidents caused by geological hazards with more than 75%. However, in case of meteorological and climatic natechs, the distribution shifts towards incidents involving aboveground storage tanks. About 50% of meteorological and 40% of climatic natechs occurred at such tanks, followed by pumping and metering stations with more than 20%. The total amount of hazardous substance released due to the natech incidents was about 50,875 m^3 (320,000 barrels) resulting in 590 million USD economic damage.

The overall analysis showed that:

- There is a tendency to underreport natural hazards as causes of incidents.
- Although they occur less frequently, the consequences of natechs can be comparatively more significant than for other pipeline incidents.
- The natural hazard damage susceptibility of pipeline systems differs with system type.
- Natural hazards do not impact all pipeline system parts equally and some parts are more and even sometimes only susceptible to selected types of natural hazards.
- Impact mechanisms at pipeline system parts other than the pipe run are not specific to pipelines and are similar to their counterparts at fixed industrial plants.
- Earthquakes are perceived to be a major threat to pipelines but historical data shows that they have not or very rarely triggered natech incidents in hazardous liquid transmission pipelines.
- Besides directly triggering incidents, natural hazards can also aggravate other incidents by accelerating causes, facilitating transport of spilled substances, or hampering response and recovery operations.
- Slow onset hazards and the variation in time of some natural hazards should be considered during the design and operation of pipeline systems, which typically have a very long operational life.
- Regulatory measures for the construction and operation of pipeline systems that consider possible time-varying natural hazard risks and impose comprehensive reporting obligations are necessary for the proper prevention and mitigation of pipeline natechs.
- Detailed incident and natural hazard data should be made available for the proper analysis of pipeline natech incidents, especially for regional or global studies.

- Besides data availability, data quality and explicit data limitations are equally important and should be carefully evaluated during the analysis.
- Pipeline operators should periodically update and complete incident reports if previously unknown or more accurate information becomes available, and competent authorities should encourage and actively follow this process.
- In order to support the lessons learning process, operators should be encouraged to also share information on near misses or incidents below the reporting threshold.

For this study, a database-driven incident data analysis system was developed to rapidly review, categorise, and query incident records according to their causes and consequences, and link them to related supplementary data. The system provides an automated pre-selection of incidents of potential interest using data mining methods. This can be supplemented by an expert review for manual confirmation of data accuracy, which can be carried out by multiple experts simultaneously.

Using this analysis system, about 1,400 fully reviewed and categorised oil and natural gas transmission pipeline natech records were identified from the European and U.S. incident data. Similarly, approximately 2,150 natural gas distribution incidents were also identified as possible natechs and are ready for more detailed peer-review. In addition to onshore incidents, all data sets include offshore incidents, as well. Therefore, the occurrence mechanisms and consequences of offshore pipeline natechs can be studied. As a by-product of the data collection process, the database furthermore includes over 800,000 U.S. National Response Centre incident reports from all causes in industrial and transportation activities, which are automatically classified in the same way as the pipeline incident records. The database is available for future studies and is especially useful for providing case-specific natech data, which is scarce in the scientific literature and in the existing accident databases.

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1. Introduction

Natural events such as earthquakes, floods, and lightning can cause accidents in oil and gas transport pipelines with potentially adverse secondary consequences on the population, the environment, or the industrial activity itself. Such accidents are commonly referred to as *natech* accidents. In order to better understand the dynamics and possible impact of pipeline natech accidents, Action A6 under the EPCIP 2012 Programme aims at analysing accidents caused by natural disasters in oil pipelines.

In the first year of the study, pipeline incident data sources were evaluated and data was collected for further analysis to identify the main accident triggers, system strengths and weaknesses, consequences and lessons learned. A database-driven incident data analysis system was developed to rapidly review and categorise the vast amount of incident records according to their causes, dynamics and consequences. Using an automated data-mining process followed by a peer-review of the data, the pipeline natechs in the database were identified. Because publicly available European pipeline incident data was limited and data on individual accidents of concern for the study was scarce, public U.S. pipeline incident data was included in the study to obtain information beneficial for the safety of pipeline systems in Europe. The features of the developed database, details of the collected data, the results of the preliminary analysis which aimed to reveal the trend of both oil and natural gas pipeline natechs, and the types of natural hazards triggering these incidents can be found in the first year study report (Girgin and Krausmann, 2014a).

In the second year of the study, the primary focus was on the in-depth analysis of the identified natech incident data with a view to understanding impact and failure modes, environmental and human-health related consequences, and lessons learned, so that recommendations for natech scenario development in pipelines and the formulation of prevention and mitigation measures can be prepared. For this purpose, the previously identified pipeline natech incidents were studied in detail individually. For each incident, the available information from the incidents reports and related records in the database (e.g. FEMA disaster declarations, NRC notification reports) were evaluated. Supplementary information from scientific publications, technical reports, newspaper articles, and online resources was also collected and added to the study repository.

This report discusses the European and U.S. oil and hazardous liquid pipeline natechs incidents identified in the study and provides results of the detailed analysis with historical trends, statistics, and maps. Special emphasis was given to the affected specific components of the pipeline network, which is divided into four main categories: 1) main pipeline body including valve sites, 2) aboveground storage tanks, 3) pumping/metering stations, and 4) terminals/tank farms. Differences in natech trends with respect to location in the pipeline network and natural hazard types were examined. Similarly, the distribution of property damage and the amount of spilled substance are also reported. Finally, natural hazard impact and damage modes of the natech incidents extracted from the database are provided.

The European oil and petroleum product pipeline incident data originating from CONCAWE incident reports and its analysis are covered in Chapter 2. The U.S. oil and hazardous liquid pipeline incident data obtained from the PHMSA incident reports and the detailed analysis is discussed in Chapter 3. The report concludes with the overall findings of the study and recommendations given in Chapter 4.

2. CONCAWE Oil Pipeline Natech Incidents

The primary data source for crude oil and petroleum product transmission pipeline incidents in Europe is the incident inventory of the Conservation of Clean Air and Water in Europe (CONCAWE) oil pipeline management group. In 1963, a small group of leading oil companies established CONCAWE to carry out research on environmental issues relevant to the oil industry (CONCAWE, 2010a). Its membership has broadened in time to include most of the oil companies operating in Europe and it currently has 43 members representing practically 100% of the total crude oil refining capacity within the European Union (CONCAWE, 2010b). The scope of CONCAWE's activities covers cross-country pipeline performance, as well. For this purpose, CONCAWE collects spillage data on European cross-country oil pipelines since 1971 with particular regard to spillage volume, clean-up and recovery, environmental consequences and causes of the incidents (CONCAWE, 2013).

The CONCAWE inventory covers pipelines that are:

- Used for transporting crude oil or petroleum products,
- Have a length of 2 km or more in the public domain,
- Run cross-country, including short estuary or river crossings (excluding under-sea pipeline systems, lines serving offshore crude oil production facilities and offshore tanker loading/discharge facilities),

Pumping stations, intermediate above-ground installations and intermediate storage facilities are included, but origin and destination terminal facilities and tank farms are excluded. The minimum reportable spillage size is 1 m³. In case of exceptional safety or environmental consequences, lower spill volumes are also reported.

The geographical region covered by the inventory includes OECD Western Europe countries (18 founding countries, except Turkey), the Czech Republic, Hungary, Slovakia, and Croatia (CONCAWE, 2013). As of 2012, the pipeline network covered by CONCAWE includes 145 pipeline systems split into 664 active sections with a total length of 35,336 km. In the CONCAWE reports, the pipelines are grouped according to the type of product transported and distinguished as crude oil, heated black products (hot oil), and white products (e.g. naphtha, gasoline). The total length of crude oil pipelines is about 10,000 km, whereas for the white product lines the total length is slightly less than 25,000 km. Hot oil pipelines were increasingly taken out of service in the last decades and currently only 60 km remain in operation (CONCAWE, 2013). The current map of the crude oil and oil product pipelines including associated operational refineries in Europe is given in Figure 2.1.

The complete CONCAWE incident database is not publicly available. However, yearly statistical *summary* reports were published by CONCAWE starting from 1971, which include short descriptions of incidents that occurred within the reporting year and provide overall statistical analysis. More detailed time-series analyses of the incidents are supplied as quinquennial performance reports (CONCAWE, 1998; CONCAWE, 2002; CONCAWE, 2011). The *performance* reports include a historical analysis of the reported incidents with respect to selected criteria such as spillage volume, hole size, part of facility where the spillage occurred, environmental impact, and method of spillage discovery.

Figure 2.1. Map of CONCAWE crude oil and oil product pipelines (CONCAWE, 2014a)

Although incident-specific details are not available, a general analysis of spillage causes is also provided. Yearly and quinquennial reports classify spill causes as five major categories, which are mechanical failure, operational errors, corrosion, natural hazards, and third-party activities. There is only one natural hazard category that is defined as “failures resulting from a natural occurrence such as land movement, flooding, lightning strike, etc.”, and therefore covers all pipeline natechs.

In the first year of the study, CONCAWE yearly statistical summary reports were available online only for recent years. Therefore, the previous analysis was based on the limited information available in the latest performance report that covers a period of 40 years from 1971 to 2010. Among the 478 reported spillage incidents due to all causes, 15 natech incidents were identified based on spill cause categories but only basic information was provided (Girgin and Krausmann, 2014a).

Recently, extracts of yearly summary reports containing detailed descriptions of the circumstances and consequences of each incident were published by CONCAWE as a series of reports entitled “Performance of European cross-country oil pipelines – Detailed description of reported spillages” and made available online. The series includes four reports for the following time periods:

- 1971-1983 (CONCAWE, 2014b)
- 1984-1993 (CONCAWE, 2014c)
- 1994-2004 (CONCAWE, 2014d)
- 2005-2011 (CONCAWE, 2014e)

In addition to detailed incident descriptions, the reports also provide structured information on pipe characteristics, estimated total cost of damage, and clean-up period. But they do not supersede performance reports completely, because there are some incident-specific data that are only available in the performance reports, such as pipe age. Therefore, the summary and performance reports complement each other.

By using the more detailed information provided in the incident narratives, additional data was collected to refine and correct existing data from the previously identified CONCAWE crude oil and petroleum product transmission pipeline natech incidents. Additionally, all incident descriptions available in the description reports were reviewed and 5 additional incidents having causes related to natural hazards were identified, which were originally categorised as non-natural hazard related incidents. These additional 5 natech incidents were also included in the analysis. With the inclusion of 2011 and 2012 data, the total number of reported incidents increased to 497.

Information on the 20 CONCAWE natech incidents is provided in Section 2.1. That section includes descriptions of the identified natech incidents as specified in the recent reports with additions from other resources when available. The analysis of the natech incidents, including pipeline specifications, spill characteristics, and estimated cost of damage is given in Section 2.2.

Because CONCAWE reports do not provide the date (available only for a limited number of incidents), location, and operator information for the incidents, the incidents are cited by the unique spillage id used in the reports.

2.1. Descriptions of Natech Incidents

Descriptions of crude oil and petroleum product transmission pipeline natech incidents identified in the incident records reported to the CONCAWE inventory are listed below in chronological order. For each incident, the occurrence date, type of pipeline facility, diameter of the pipeline, natural hazard triggering the incident, type of substance, volumetric amount of spill, and volume of substance that is recovered are provided. Incidents which were originally not categorised as natural hazard related are marked with an asterisk. For selected incidents, additional information including the country of occurrence was supplemented using the gasoline pipeline historical experience report of the U.K. Health and Safety Executive (HSE, 1999).

Incident 48

1974/11/18, Pipeline (28"), Subsidence, Crude oil (100 m^3 spilled, 60 m^3 recovered)

The fracture due to land subsidence resulted from the collapse of mine workings. The mining industry is able to predict with considerable accuracy the area likely to be affected by, and the timing of, such earth movement, and close liaison with the authorities concerned will eliminate most of this type of hazard to a buried pipeline. Nevertheless, additional precautions have been taken by the pipeline operators themselves (CONCAWE, 2014b).

Incident 98

1976/11/04, Pipeline (24"), Landslide, Crude oil (200 m^3 spilled, 200 m^3 recovered)

The pipe fractured due to landslip which occurred during a period of prolonged and abnormally heavy rainfall. An adjacent railway track was also washed out. The pipeline was diverted away from the danger zone (CONCAWE, 2014b).

Incident 99

1976/11/11, Pipeline (10"), Landslide, Hot fuel oil (50 m^3 spilled, 25 m^3 recovered)

The pipe fractured due to a landslide which occurred during a period of prolonged and abnormally heavy rainfall. The site was stabilised by extensive drainage works (CONCAWE, 2014b).

Incident 114

1977/11/11, Pipeline (12"), Landslide, Gasoil (103 m^3 spilled, 103 m^3 recovered)

Abnormally heavy rain caused a landslide and the pipeline ruptured at a weld. The outflowing oil was partly recovered and partly disposed of by removing the contaminated soil from the site, leaving no adverse effect on the environment (CONCAWE, 2014b).

Incident 115

1977/10/09, Pipeline (20"), Flood, Crude oil (550 m^3 spilled, 50 m^3 recovered)

Exceptionally heavy rainfall caused a river to overflow, washing away one of its banks at the location of a pipeline crossing which subsequently broke. The recovery of the oil spilled was seriously hindered by the large area inundated and could only progress effectively after the river had returned to its normal course. A new crossing was installed with a lower elevation (CONCAWE, 2014b).

Incident 116

1977/01/11, Pipeline (24"), Storm, Crude oil (600 m³ spilled, 575 m³ recovered)

In a heavy storm a suspension bridge supporting a pipeline crossing over a river collapsed. The pipeline ruptured and out-flowing crude oil was carried by the river to a nearby lake. Rapidly mobilised clean-up crews constructed interceptor dams in the river with built-in culverts to allow passage of uncontaminated water. A number of in-series floating barriers were installed in the lake at the entrance of the river with skimmers removing oil from the water surface. The river and lake bands were cleaned up by high pressure water spraying combined with the application of absorbents which were subsequently encircled and recovered. To restore a possible depletion of the fish population, the river was restocked with additional species. The estimated total cost (approximately 14 million EUR in 2012) includes a temporary new crossing (CONCAWE, 2014b).

Incident 123*

1977/05/06, Pipeline (20"), Flood, Naphtha (2,530 m³ spilled, 30 m³ recovered)

The incident involved the rupture of the pipe crossing a large river in France. Third parties had for some time been extracting large quantities of gravel from the river bed and this is thought to have caused a change in level of the river bed and possibly a change of the current flow at the pipeline crossing. At the time of prolonged heavy rainfall the river was flowing very fast and erosion of the river bed exposed the pipe, causing it to span and rupture. Isolation valves on either side of the river crossing were shut after 40 minutes. The light product was moved away by the fast running water and dispersed by evaporation. Almost the total quantity of product spilled was lost to the environment (2,500 m³ out of 2,530 m³ gross spillage). A new river crossing was installed with adequate precautions to prevent recurrence of similar incidents in future (HSE, 1999; CONCAWE, 2014b).

Incident 134

1978, Pipeline (16"), Flood, Crude oil or product (400 m³ spilled, 150 m³ recovered)

Heavy rainfall under-washed a pipeline which failed in bending (CONCAWE, 2014b).

(No detailed description is available)

Incident 154

1980, Pipeline (12"), Subsidence, Hot fuel oil (111 m³ spilled, 99 m³ recovered)

Movement of the ground caused cracking of a concrete support block. Damage was increased as a result of longitudinal pipe due to heating, leading to abrasion of the coating exposure of the bare metal. The pipe failure was gradually due to the combination of corrosion and friction (CONCAWE, 2014b).

(Description is garbled in the original report)

Incident 169

1980, Pipeline (26"), Landslide, Gasoil (125 m³ spilled, 80 m³ recovered)

The incident was caused by a landslide, which led to a fracture at a welding joint of the pipeline. The incident occurred during refilling, temporarily inhibiting the volume balance leak detection system installed (CONCAWE, 2014b).

Incident 170

1981, Pump station (24"), Frost heave, Hot fuel oil (30 m³ spilled, 20 m³ recovered)

The incident occurred in a pump station. A drain-pipe was lifted by a stone, which itself was moved as a consequence of frost heave. The shifting of the drain-pipe caused a crack at the connection of the drain-pipe and the main line (CONCAWE, 2014b).

Incident 200*

1984, Pipeline (16"), Hot weather, Crude oil (10 m³ spilled, 10 m³ recovered)

A ball valve, which did not seal properly in one direction, allowed the filling of a scraper trap. It was assumed that due to solar radiation an overpressure developed, which resulted in the spillage from the scraper trap (CONCAWE, 2014c).

Incident 217*

1986/06/16, Pipeline (24"), Subsidence, Gasoil (292 m³ spilled, 288 m³ recovered)

The incident was caused by a broken gasket between insulating flanges near a valve in a 24" product line close to a river crossing in Netherlands. It is assumed that settlement of the line caused a 1 mm gap to open up between the flanges. The leak was first discovered by a mechanic performing maintenance work in that rural location. The automatic leak detection system did not detect the leak. The leak had occurred for less than 1 day, so it was not discovered by helicopter surveillance (one every 10 days) or by inspections by car/foot every 3 months. The flow rate at the time of incident was 1,000 m³/h with a pressure of 30 bar. An area of 3,000 m² was affected by the leak and about 2,000 m³ of contaminated soil had to be removed (HSE, 1999; CONCAWE, 2014c).

Incident 232

1987, Pipeline (12"), Landslide, Naphtha (12 m³ spilled, 2 m³ recovered)

The spillage occurred where a 12" naphtha pipeline traverses a steeply sloping field in hilly countryside. A third party reported smelling light hydrocarbons and an intermediate investigation discovered a 20 l/hr leak. Downhill slippage of the ground had overstressed the pipeline causing a hairline crack 70 mm long in the pipe wall. The spillage contaminated a patch of agricultural land for a period and local ground water was also affected. Oil recovery was hampered by the lightness of the product and only some 2 m³ out of the gross spillage of 12 m³ was collected (CONCAWE, 2014c).

Incident 241

1988/09/05, Pipeline (10"), Landslide, Light fuel oil (305 m³ spilled, 300 m³ recovered)

The spillage occurred where a 10" products pipeline in a rural area crosses under a river onto a tongue of land bordered by another river in Italy. In the region of one of the river banks, the ground containing the pipeline was subject to movement due to creep flow of the land. The pipeline under the river itself remained as a fixed point and the change in direction of the pipeline at the angle of ascent from the river crossing became deformed and overstressed. A 160 mm rupture occurred which was detected not long after the pressure discrepancies were noticed by the pipeline operators who initiated shut down and isolation. The leakage of light fuel oil was initially stemmed by installing a collar over the rupture. Some of the released oil reached the river and another river downstream. Temporary barriers were set up on the rivers and a large scale effort was mounted to trap and collect the free oil. At the same time, clean-up of the riverside was attended to, and when this was completed, residual oil bloom formation on the rivers was dealt with over a period of time using a series of barriers and absorbent materials. The 300 m³ of oil recovered altogether was safely disposed of at controlled disposal and incineration sites. The overall clean-up time was 54 days and the pipeline shut-down for realignment and repair was 5 days (CONCAWE, 2014c).

Incident 275*

1991/05/05, Pipeline (20"), Subsidence, Gasoline (275 m³ spilled, 157 m³ recovered)

Subsidence in a coal mining region in Germany caused an 80 cm long crack in a pipeline from which 275 m³ gross of product leaked. Because of the known risk of progressive subsidence in this area the pipeline was specifically instrumented and monitored to detect any effects of ground movements. The mining activities in and around the particular area of rupture had come to an end more than a decade ago. Neither during the period of mining activities nor thereafter had any indications of trouble been received. Incomplete data monitoring techniques have to be assumed as the probable reason for the undetected tensions that eventually caused the rupture. When the pipeline ruptured, the leakage was detected by the control center within a few seconds, located to within 300 m by the automatic leak detection system and emergency shutdown was immediately initiated. Pumps were switched off and all dampers closed within 6 minutes, isolating the pipeline. The pipeline ran about 40 m parallel to a motorway from Germany to Holland. Released gasoline discharged down the embankment of the motorway into the motorway sewage systems and from there into streams. As a result, product entered waterways 1 km away and travelled through some residential areas. The motorway was closed on both sides and the emergency services monitored product vapors in air. Respiratory protection had to be worn because of the high concentration of the gasoline in air. Product recovery work was also hampered due to the high risk of ignition of the explosive gasoline atmosphere surrounding the incident area. The pipeline was repaired within 4 days and returned to service for extensive testing procedures over a number of weeks. The environmental damage limitation and clean-up activities were more extended, extensive and costly, recovering some 157 m³ of spilled product. Some 20,000 tons of soil had to be excavated and taken away for microbiological remediation at a specially prepared place (HSE, 1999; CONCAWE, 2014c).

Incident 305

1992, Pipeline (12"), Flood, Heating oil (75 m³ spilled, 0 m³ recovered)

Flooding caused displacement of the earth around the pipeline leading to a circumferential crack in the pipe wall. A spillage of about 75 m³ gross of heating oil occurred. No recovery of the spillage was reported, nor could any specific details of oil clean-up be distinguished from the general repair of the flood damage which was widespread. The pipeline was out of service for nearly three months. The spilled oil affected the local soil for less than six months (CONCAWE, 2014c).

Incident 314

1993, Pipeline (26"), Landslide, White product (10 m³ spilled, 3 m³ recovered)

A 10 m³ gross spillage occurred in mountainous terrain due to earth movement associated with heavy rain which also resulted in regional flooding in lower lying areas. The movement caused cold bending of the pipeline leading to a hairline crack over part of its circumference on the outside of the bend. As well as local soil pollution, some groundwater contamination occurred and precautions were taken to protect drinking water. The clean-up involved forming shallow channels and collecting oil flushed out by water washing. Some contaminated soil was removed and safely disposed of offsite. By these means, some 3 m³ of the spillage was recovered (CONCAWE, 2014c).

Incident 326*

1994, Pump station, Hot weather, Crude oil (2 m³ spilled, 0 m³ recovered)

Due to a fire detection instrument anomaly which occurred on a particularly warm day, the procedure for extinguishing a fire in a pump station was activated. The water used filled up the slop tank which overflowed, resulting in the spillage of the contents, 2 m³ of crude oil. Difficulties were experienced in over-riding the anti-fire system, and the continuing flow of fire water caused an area outside the pump station to be polluted including a small amount of oil in an adjacent canal. Clean-up took 3 days (CONCAWE, 2014d).

Incident 402

2002, Pipeline (24"), Subsidence, White product (250 m³ spilled, 230 m³ recovered)

A slow movement of earth caused a 1" drain line to be pushed away from the body of an isolating valve causing the joint to rupture. 250 m³ of white product was spilled. 230 m³ of free product was recovered but an area of 5,000 m² was contaminated in an industrial area. Clean up was expected to take over one year (CONCAWE, 2014d).

2.2. Analysis of Natech Incidents

According to the latest CONCAWE performance report that provides a statistical summary of reported spillages between 1971 and 2012 in Europe, there were 497 reported spill incidents over the 42-year survey period (CONCAWE, 2013). Out of these, there are 20 spill incidents identified as related to natural hazards, which is equal to 4% of all reported incidents.

Summary data on these natech incidents are summarized in Tables 1-3. Short cause descriptions, cause classifications according to CONCAWE, and natural hazards assigned by this study according to the incident narratives are given in Table 2.1. Table 2.2 lists substance type, incident location and pipeline characteristics, including diameter, wall thickness, material specification, installation year, and age at the time of incident. Failure modes of the incidents, spilled and recovered substance amounts, and environmental pollution indicators are given in Table 2.3.

The majority of the natechs occurred in the 1970-80's and recent natechs are rare, with no reported event in the last decade (Figure 2.2). Over the 42 year period covered by the data, there are 27 years without any natech incident (65%) and years with more than one natech incident are scarce (7%). The yearly average natech occurrence rate is calculated as approximately 0.5 incidents/year. The natural hazard classification used in this study can be found in Appendix A.

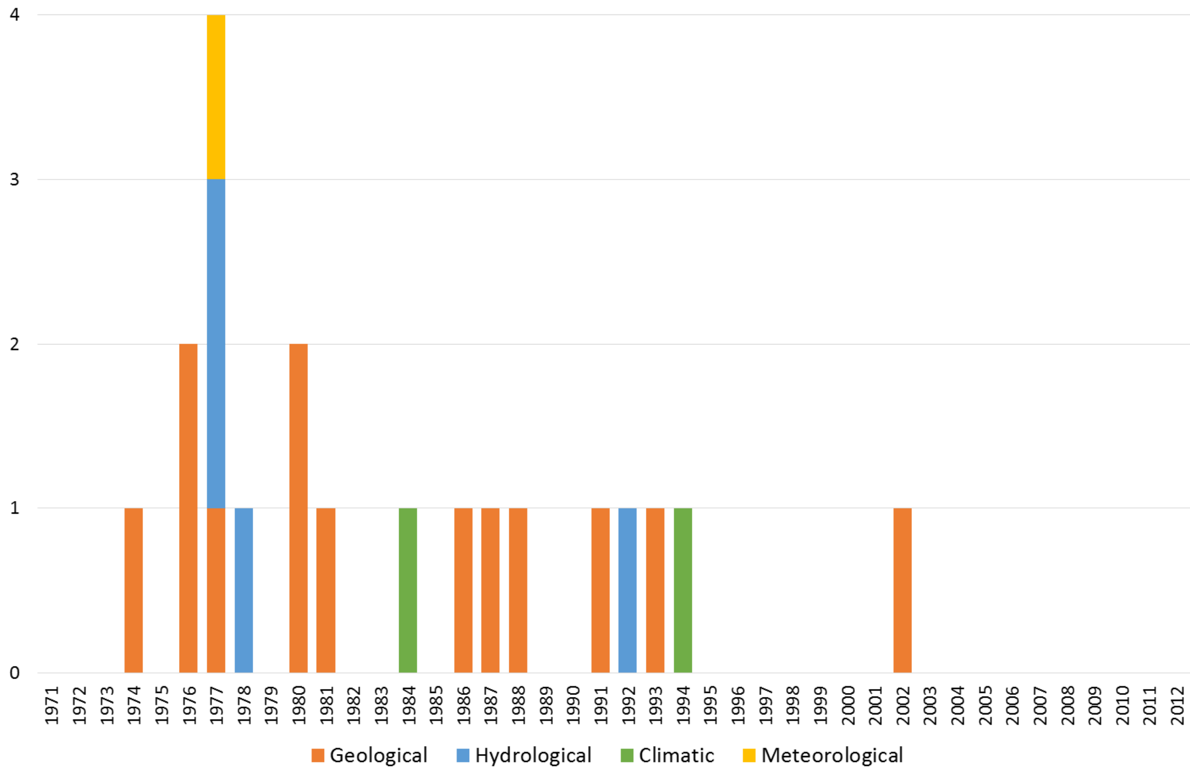


Figure 2.2. Yearly distribution of CONCAWE natech incidents with respect to natural hazard

Incident locations are not indicated in the reports, but it is stated that no less than 10 of the incidents occurred in the same country. It is attributed to be a direct consequence of the difficult terrain and hydrological conditions that apply to a significant part of that country's pipeline network (CONCAWE, 2011). Although this list is not exhaustive, countries with pipeline incidents identified by using information from other sources include France, Italy, Germany, and The Netherlands.

Table 2.1. Cause descriptions of the CONCAWE natech incidents

Spill ID	Year	Cause Description	CONCAWE Cause Classification	Assigned Natural Hazard
48	1974	Overstress due to land subsidence from the collapse of mine workings	Ground movement	Subsidence
98	1976	Landslip due to abnormal rainfall	Ground movement (Subsidence)	Landslide
99	1976	Landslide due to abnormal rainfall	Ground movement (Subsidence)	Landslide
114	1977	Landslide due to abnormal rainfall	Ground movement (Landslide)	Landslide
115	1977	River overflow and bank washing due to heavy rain	Ground movement (Flooding)	Flood
116	1977	Collapse of suspension bridge supporting the pipeline in a heavy storm	Other natural hazard	Storm
123*	1977	Erosion of river bed during prolonged heavy rainfall at pipeline crossing	Third party activity (Incidental)	Flood
134	1978	Under-washing of pipeline due to heavy rainfall	Ground movement (Flooding)	Flood
154	1980	Subsidence at concrete support followed by abrasion/corrosion	Ground movement (Subsidence)	Subsidence
169	1980	Excessive pipe stress due to landslide	Ground movement (Landslide)	Landslide
170	1981	Crack at weld of drain line due to movement caused by frost heave	Other natural hazard	Frost heave
200*	1984	Spillage from scraper trap due to overpressure from solar radiation	Operational (System)	Hot weather
217*	1986	Failure of gasket at insulating flanges due to settlement of the line	Mechanical failure (Construction)	Subsidence
232	1987	Excessive pipe stress due to landslide	Ground movement (Landslide)	Landslide
241	1988	Deformation and overstress due to ground movement near river banks	Ground movement (Landslide)	Landslide
275*	1991	Subsidence in a coal mining region	Mechanical failure (Design & Materials)	Subsidence
305	1992	Displacement of soil around the pipeline due to flooding	Ground movement (Flooding)	Flood
314	1993	Earth movement due to heavy rain	Ground movement (Landslide)	Landslide
326*	1994	Fire detection instrument anomaly on a particularly warm day	Operational (System)	Hot weather
402	2002	Displaced isolating valve drain line by slow movement of earth	Ground movement (Earthquake)	Subsidence

Table 2.2. Pipeline characteristics of the CONCAWE natech incidents

Spill ID	Year	Substance	System Part	Item	Diameter (")	Thickness (")	Specification	Age at Incident	Installation Year
48	1974	Crude oil	Pipeline	Pipe run	28	0.34	5L X52	16	1959
98	1976	Crude oil	Pipeline	Pipe run	24	0.28	5L X52	10	1967
99	1976	Hot fuel oil	Pipeline	Pipe run	10	0.20	5L X52	-	-
114	1977	White product (Gasoil)	Pipeline	Pipe run	12	0.25	5L X42	19	1959
115	1977	Crude oil	Pipeline	Pipe run	20	0.44	5L X52	13	1965
116	1977	Crude oil	Pipeline	Pipe run	24	0.47	5L X52	11	1967
123*	1977	White product (Naphtha)	Pipeline	Joint	20	0.47	5L X60	9	1969
134	1978	Crude oil or product	Pipeline	Pipe run	16	0.34	5L X52	14	1965
154	1980	Hot fuel oil	Pipeline	Pipe run	12	0.25	5L X52	15	1966
169	1980	White product (Gasoil)	Pipeline	Joint	26	0.38	5L X52	18	1963
170	1981	Hot fuel oil	Pump station	Auxiliary piping	-	-	-	14	1968
200*	1984	Crude oil	Pipeline	Pipe run	16	0.22	5L X52	21	1964
217*	1986	White product (Gasoil)	Pipeline	Joint	24	0.50	5L X46	26	1961
232	1987	White product (Naphtha)	Pipeline	Pipe run	12	0.25	5L X52	21	1967
241	1988	White product	Pipeline	Pipe run	10	0.22	5L X52	23	1966
275*	1991	White product	Pipeline	Pipe run	20	0.28/0.56	5L X52/X42	24	1968
305	1992	White product (Heating oil)	Pipeline	Pipe run	12	0.25	5L X52	28	1965
314	1993	White product	Pipeline	Pipe run	26	0.28	5L X52	31	1963
326*	1994	Crude oil	Pump station	Slop tank	-	-	-	-	-
402	2002	White product	Pipeline	Auxiliary piping	24	0.32	5L X46	39	1964

Table 2.3. Spill characteristics of the CONCAWE natech incidents

Spill ID	Year	Failure Mode	Spilled (m^3)	Recovery (m^3)	Loss (m^3)	Land use	Soil pollution	Water pollution	Clean-up (days)
48	1974	Fracture	100	60	40	-	Some	Drainage ditches	3
98	1976	Fracture	200	200	0	-	Some	No	20
99	1976	Fracture	50	25	25	-	Some	No	8
114	1977	Rupture at weld	103	103	0	-	Yes	No	5
115	1977	Rupture	550	50	500	Residential low density	Agricultural land	River	3
116	1977	Rupture	600	575	25	Residential low density	Banks of river and lake	River and lake	~49
123*	1977	Rupture	2,530	30	2,500	Residential low density	Banks of river	River	69
134	1978	Bend failure	400	150	250	Residential low density	Yes	River	180
154	1980	Rupture	111	99	12	Residential low density	10,000 m^2	Yes	20
169	1980	Crack at weld	125	80	45	Residential low density	Yes	Stream and sea	15
170	1981	Crack at weld	30	20	10	Industrial or commercial	Yes	No	~120
200*	1984	Overpressure	10	10	0	Residential low density	50 m^2	No	1
217*	1986	Gasket failure	292	288	4	Residential low density	3,000 m^2	No	350
232	1987	Hairline crack	12	2	10	Residential low density	2,000 m^2	Groundwater	40
241	1988	Rupture	305	300	5	Residential low density	5,000 m^2	Rivers	54
275*	1991	Crack	275	157	118	Residential low density	14,000 m^2	Stream	> 30
305	1992	Circumferential Crack	75	0	75	Residential low density	Yes	No	> 30
314	1993	Hairline crack	10	3	7	Forest hills	Yes	Yes	90
326*	1994	Overflow	2	0	2	Industrial or commercial	100 m^2	Canal	3
402	2002	Rupture at joint	250	230	20	Industrial or commercial	5,000 m^2	No	> 365

Geological hazards were the primary trigger of pipeline natechs in Europe with 65%, followed by hydrological hazards with 20%. 10% of the incidents were related to climatic hazards (Figure 2.3). Although all hydrological incidents were triggered by flooding due to heavy rainfall, there was only one incident solely having meteorological origin, which was caused by a heavy storm (Incident #116).

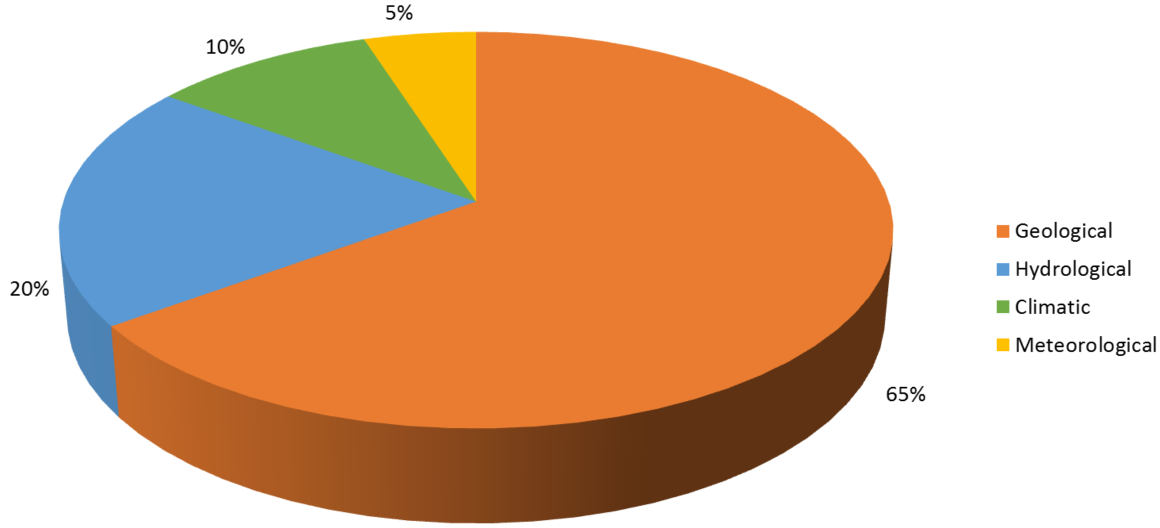


Figure 2.3. Distribution of CONCAWE natech incidents by natural hazard

About 55% of the geological hazards were landslides, followed by subsidence with 40%. Ground movement due to heavy rain was the failure mechanism in 4 landslide events (57%). In one case, creep flow of the land occurred in a region close to the banks of crossing rivers (Incident #241). For the other cases a landslide trigger was not specified. The majority of the landslide incidents resulted in pipe rupture mainly at girth welds. But hairline cracks along the pipe wall due to overstress and bending caused by the ground movement were also observed in two cases (28%). Solutions applied to prevent future incidents in the landslide areas included diversion of the pipeline away from the danger zone (Incident #98) and site stabilization by extensive drainage works (Incident #99).

Subsidence caused different types of failures, which mainly affected pipeline elements other than the pipe run. These include gasket failure at insulating flanges (Incident #217), joint failure at auxiliary piping connected to valves (Incident #412), and failure of concrete support leading to pipe failure (Incident #154). In two cases (40%), the trigger of soil subsidence was coal mining activities and the risk of progressive subsidence was known to the operators (Incident #48, #275). However, existing precautionary measures were not effective in preventing incidents. Incomplete data monitoring techniques were also reported as a factor. It is mentioned that additional precautionary measures had been initiated to overcome these problems. In addition to landslide and subsidence incidents, there was also one incident due to frost heave that resulted in a crack at a weld of a drain line at a pump station (Incident #170). No incidents related to earthquakes were found in the CONCAWE database. Likewise, there were no incidents due to soil erosion or other geological hazards, such as dents caused by rocks.

Pipe failure following the washout of the soil cover was the damage mode for all flooding incidents. In order to prevent similar incidents in future, new river crossings were installed with adequate precautions, such as deeper soil cover under the river bed. Serious problems in the recovery phase due to the large inundated area, which allowed effective clean-up only after the flow conditions returned to the original state, were reported as a difficulty specific to flood natechs (Incident #115). Limited product recovery due to a high degree of mixing and transport with the flood waters was also indicated. The incidents also highlight the importance of monitoring natural and man-made changes in the upstream sections of the water courses that can result in alterations in the flow regime at the pipeline crossings and degrade protective soil cover (Incident #123). No incidents were identified which were triggered by stream erosion/scouring under normal flow conditions.

The only meteorological incident was the rupture of the pipe due to the collapse of the suspension bridge supporting the pipeline crossing over a river (Incident #116). The high estimated cost of the incident, which is 37% of the total cost of all reported CONCAWE pipeline natechs, increases the significance of the incident.

There were two natechs triggered by climatic hazards, both of which were related to hot weather and involved piping equipment. In the first one, overpressure from solar radiation resulted in a spill from a scraper trap (Incident #200). In the second one, a fire detection instrument anomaly that occurred on a particularly warm day resulted in slop tank overflow (Incident #326). Difficulties were reported in override the anti-fire system, which facilitated the release. There are no cold-weather related natechs reported in the CONCAWE database.

The distribution of natech incidents with respect to the substance type is given in Figure 2.4. Half of the incidents occurred at white product transmission lines, whereas 35% involved crude oil and the remaining 15% heated black products (hot oil).

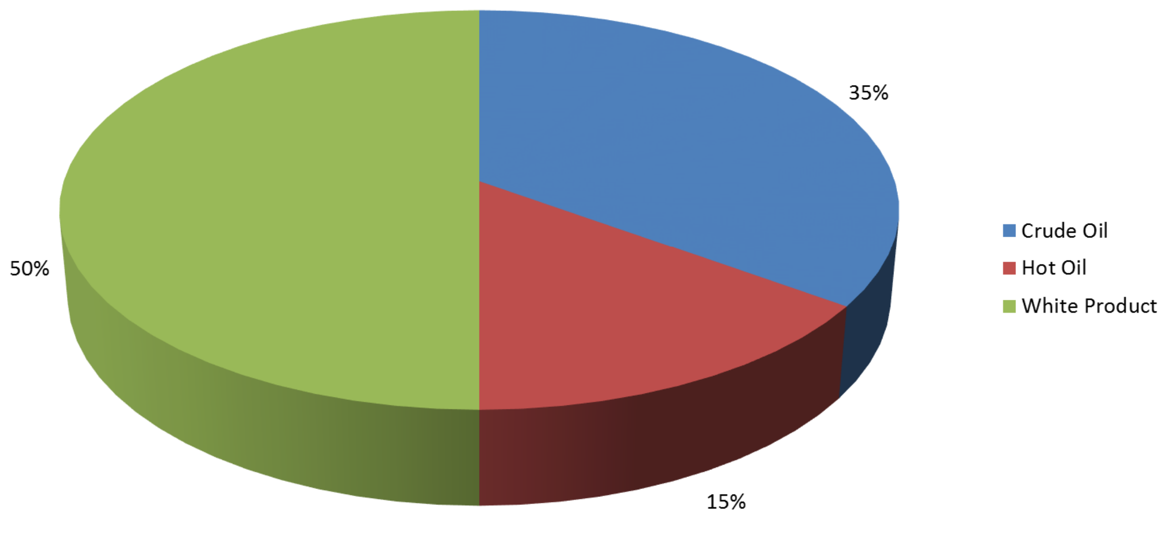


Figure 2.4. Distribution of CONCAWE natech incidents by substance type

The evolution of the length of the pipelines included in the CONCAWE inventory shown in Figure 2.5 indicates that hot oil pipelines made up only a small fraction of the existing lines at the beginning (6%) and currently they are almost extinct (< 0.05%). Since 1981, no natech incidents were observed at these pipelines. Therefore, a 35% historical share in natechs is remarkably high. The CONCAWE reports indicate that one of the reasons in the operational decline of the hot oil pipelines is generally poor reliability experienced with several of these pipelines. The comparatively high number of natechs could be related with this situation.

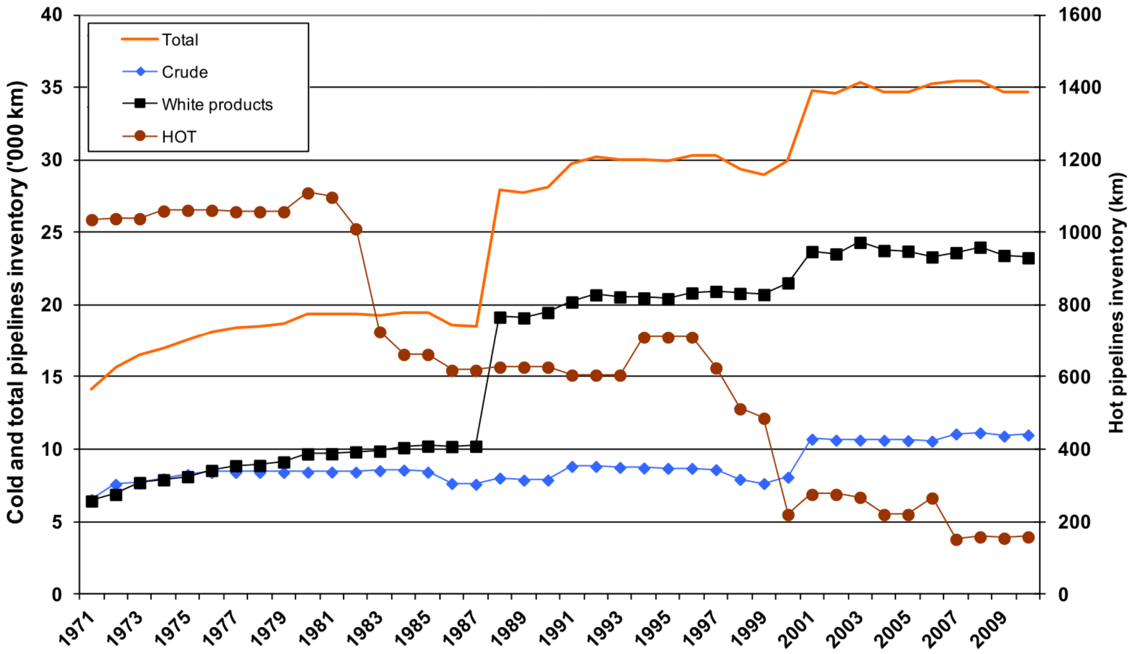


Figure 2.5. CONCAWE oil pipeline inventory and main service categories (CONCAWE, 2011)

Although incidents at pumping stations and intermediate facilities are included in the CONCAWE database, there are only two such natech events (Table 2.2). 90% of the natechs involved the pipe run of underground pipelines, whereas the remaining 10% involved pump stations (Figure 2.6).

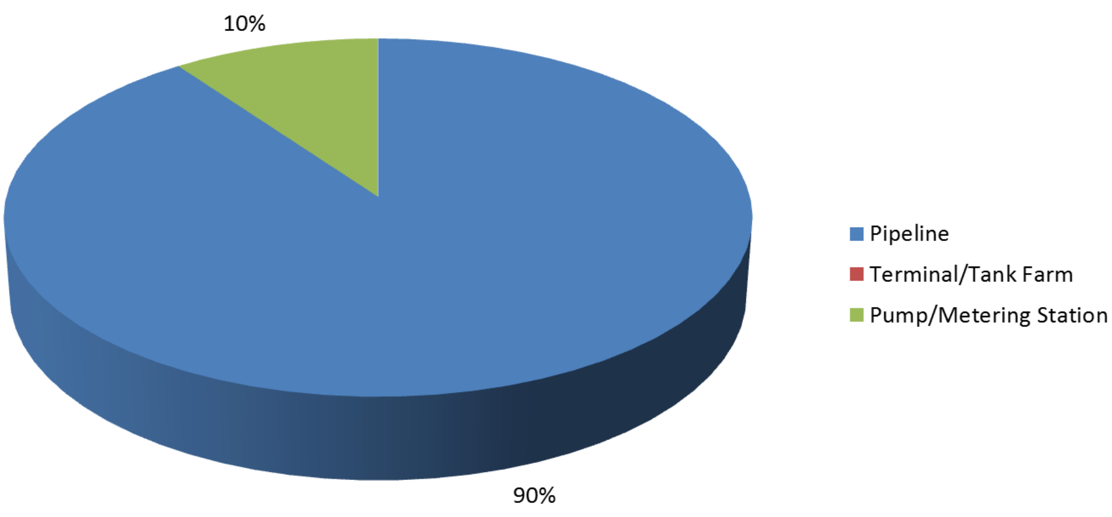


Figure 2.6. Distribution of CONCAWE natech incidents by pipeline network location

There are no reported natechs for intermediate above-ground installations and storage facilities. The distribution is significantly different in the U.S. hazardous liquid pipeline incident data in which the number of natech incidents at intermediate storage facilities is almost equal to the ones at pipeline bodies with 36% (see Section 3). The U.S. data also show that intermediate storage facilities, especially intermediate tank farms, are vulnerable to natural hazards including lightning, frost, and frost heave. However, lightning and frost incidents are not present at all in the European data. This difference could be due to different reporting criteria, however, further research and data are needed to exclude a possible lack of information or misclassification which might be another reason.

Diameter distributions at the time of the incidents are difficult to find, however the latest CONCAWE report indicates that currently 90% of the crude oil pipelines are 16" or larger up to a maximum of 48", whereas 85% of the white product lines are smaller than 16" (CONCAWE, 2013). The largest hot oil pipeline is indicated as 20". Diameters of the pipelines affected by natural hazards range from 10" to 28" (Figure 2.7). There were comparatively more natechs at small-sized pipes, including all hot oil pipeline natechs. Crude oil natechs are observed at 16" and larger diameter pipelines. Due to the low number of incidents at each diameter, the overall distribution of crude oil and white product natechs with respect to diameter is fairly uniform. There is a lack of natech incidents at very large diameters.

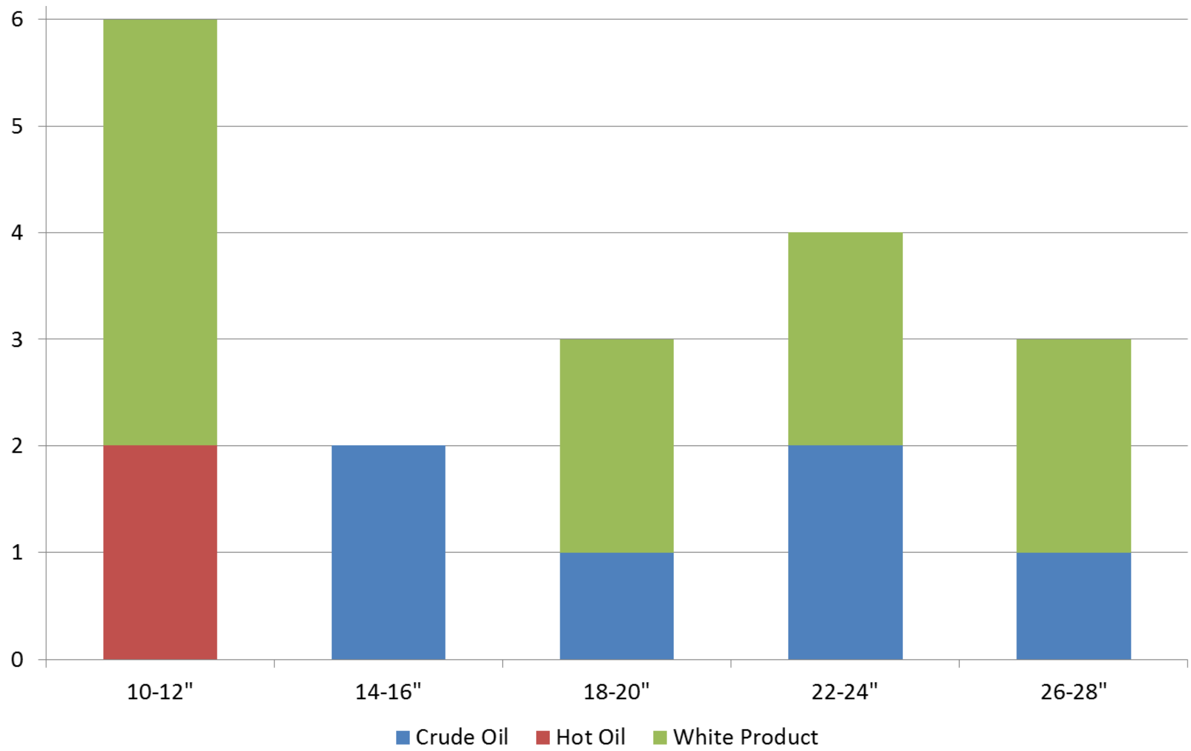


Figure 2.7. Distribution of CONCAWE natech incidents by pipe diameter and substance type

Most of the major European pipelines were built in the 1960s-1970s and currently about 60% of the pipelines are over 40 years old (CONCAWE, 2013). The distribution of the installation years of the pipelines shows that natech incidents occurred only at pipelines constructed in the 1960s (1959-1969). Hence, no natechs were reported at the newly constructed pipelines. The vast majority of the pipelines involved in the natech incidents are API 5L X52 steel pipes. Occasionally, X42, X46, and X60 pipes were also observed (Table 2.2).

The total amount of crude oil and petroleum products released to the environment due to European transmission pipeline natech incidents is 6,000 m³ (Table 2.3). 40% of the spilled amount, which is equal to 2,400 m³, was subsequently recovered. The mean spill volume per natech incident is about 300 m³. However, this number is slightly biased due to a single incident with 2,500 m³ of spill volume (Incident #123).

The median spill volume, which is more representative of the average, is 120 m³. 35% of the incidents resulted in a spill less than 100 m³, whereas spills ranging from 100 m³ to 500 m³ are 50%. Major incidents with spills over 400 m³ are all river crossing incidents, mainly triggered by floods (Figure 2.8). For one flooding incident, which had a spill volume of 75 m³, no water pollution was indicated (Incident #305). Therefore this incident might be areal flooding but not riverine flooding, resulting in less substance spilled due to the different failure mechanisms involved. Climatic natech incidents resulted in minor releases all less than or equal to 10 m³.

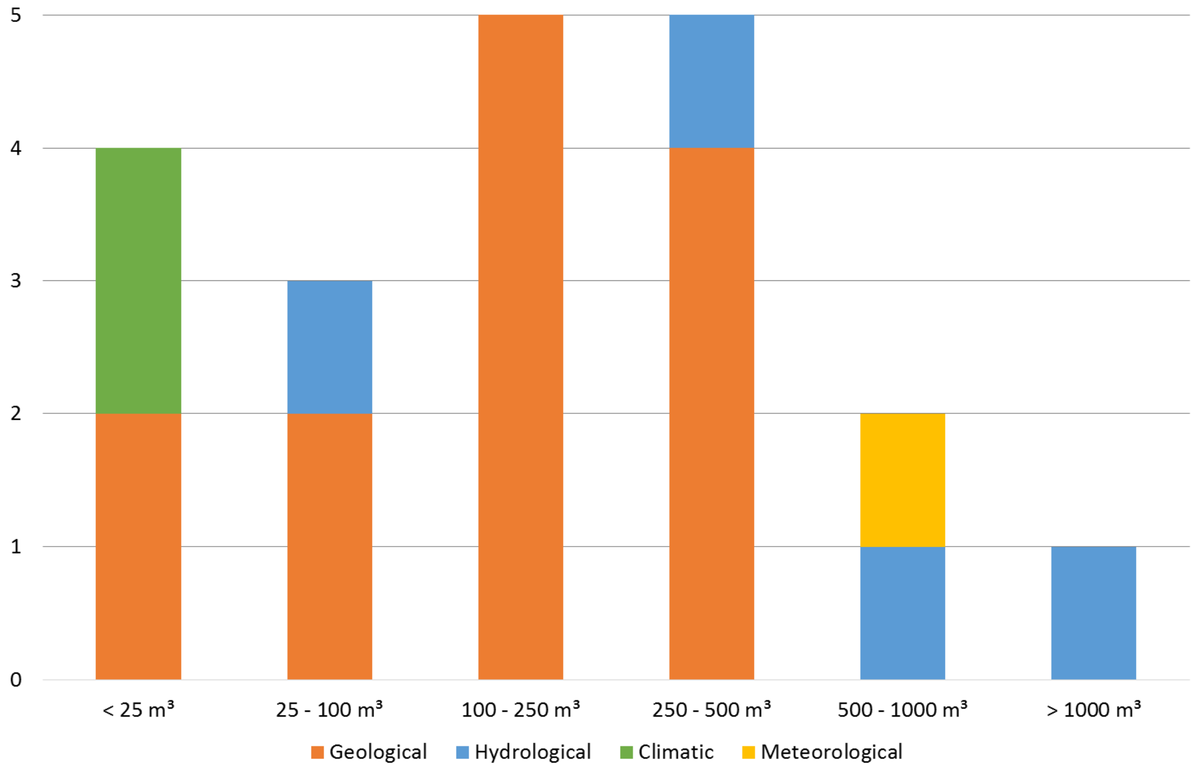


Figure 2.8. Histogram of the spill amount of CONCAWE natech incidents

All incidents resulted in varying degrees of soil pollution, including agricultural areas and banks of rivers and lakes. 60% of the incidents also caused water pollution (Table 2.3). The duration of clean-up activities ranges from one day to more than one year, the median duration being around one month. The effectiveness of clean-up efforts with respect to natural hazard types are summarized in Figure 2.9. Recovery and clean-up activities were mostly satisfactory and at least half of the released substances were recovered in 75% of the incidents. Most of the incidents, for which the recovery was not satisfactory (< 10%), are related to flooding events. As mentioned before, the rapid transport and high degree of mixing due to flood waters hampers effective clean-up and recovery.

The total estimated costs of the CONCAWE natech incidents, which are available for all but 3 incidents, are listed in Table 2.4. For the majority of the incidents, the costs were reported in British pounds effective for the year of the incident. These costs were first corrected for inflation and then converted to 2012 British pounds. Subsequently, their equivalence in 2012 Euro was calculated. Cost values which are originally reported in Euro are also corrected for inflation and converted into 2012 Euro equivalent value (Table 2.4).

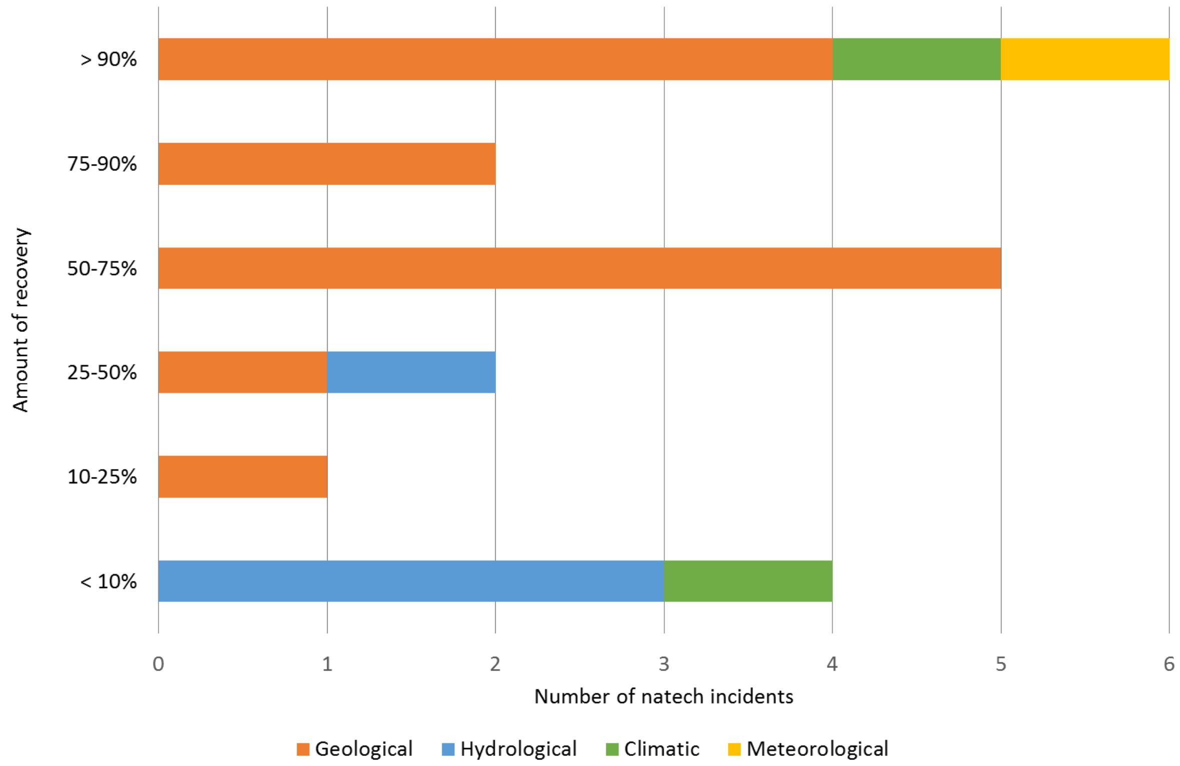


Figure 2.9. Effectiveness of clean-up efforts

Table 2.4. Estimated cost of the CONCAWE natech incidents

Spill ID	Year	Estimated cost	Estimated cost (2012)	Estimated cost (2012 €)
48	1974	52,300 £	393,000 £	485,000 €
98	1976	161,000 £	837,000 £	1,032,000 €
99	1976	96,000 £	499,000 £	615,000 €
114	1977	3,000 £	14,000 £	17,000 €
115	1977	135,000 £	606,000 £	747,000 €
116	1977	2,600,000 £	11,673,000 £	14,392,000 €
123*	1977	650,000 £	2,918,000 £	3,598,000 €
134	1978	155,000 £	643,000 £	792,000 €
154	1980	162,400 £	503,000 £	620,000 €
169	1980	574,000 £	1,778,000 £	2,193,000 €
170	1981	33,000 £	91,000 £	113,000 €
200*	1984	12,000 £	28,000 £	34,000 €
217*	1986	480,000 £	1,016,000 £	1,252,000 €
232	1987	325,000 £	660,000 £	814,000 €
241	1988	530,000 £	1,026,000 £	1,265,000 €
275*	1991	6,000,000 €	9,434,000 €	9,434,000 €
305	1992	N/A	N/A	N/A
314	1993	880,000 €	1,293,000 €	1,293,000 €
326*	1994	N/A	N/A	N/A
402	2002	N/A	N/A	N/A

All calculated costs are rounded to the nearest thousand fold for convenience.

The total estimated damage cost of all natech incidents as corrected for inflation is 38.7 million Euro (in 2012 Euro). The highest cost for a single event is 14.4 million Euro, while the mean and median costs are 1.9 million and 0.8 million Euro, respectively (in 2012 Euro). A histogram of the estimated cost of the incidents with respect to natural hazard type is given in Figure 2.10.

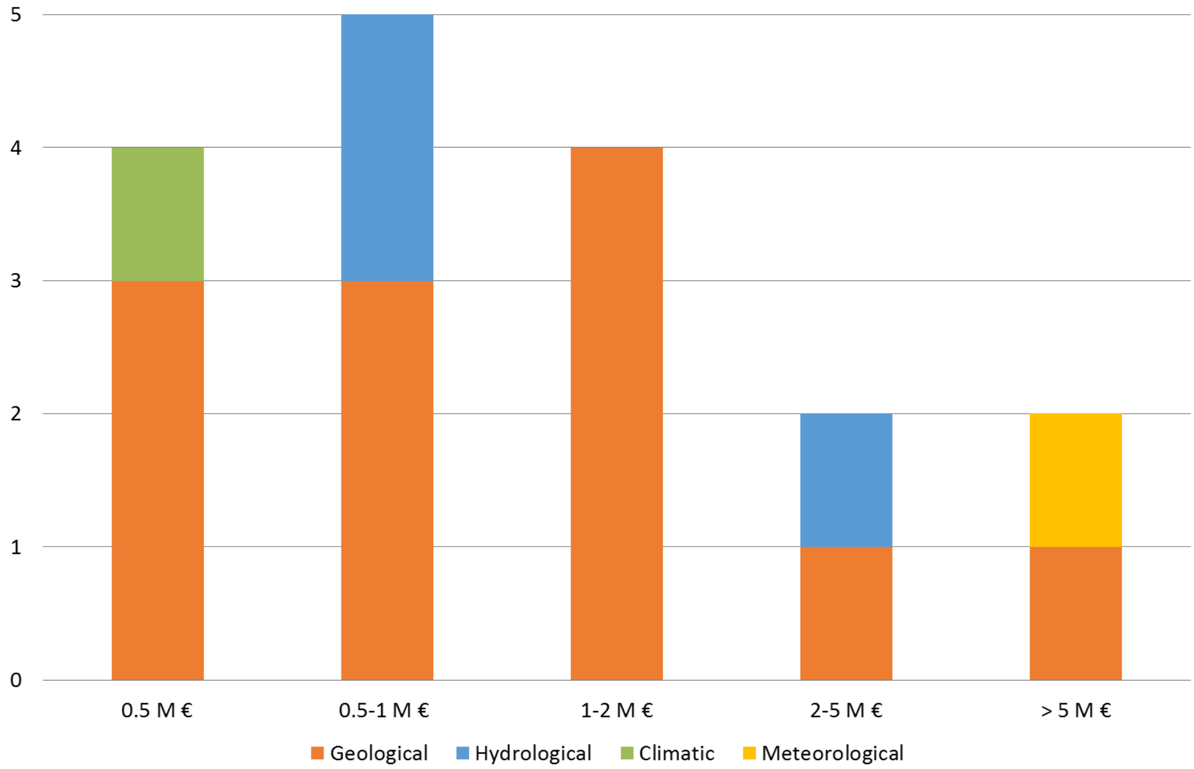


Figure 2.10. Histogram of estimated cost of CONCAWE natech incidents with respect to natural hazard type

3. PHMSA Hazardous Liquid Pipeline Natech Incidents

The Pipeline and Hazardous Material Safety Administration (PHMSA), acting through the Office of Pipeline Safety, administers the U.S. national regulatory program to assure the safe transportation of natural gas, petroleum, and other hazardous materials by pipeline. The administration develops regulations and other approaches to risk management to assure safety in design, construction, testing, operation, maintenance, and emergency response of pipeline facilities (PHMSA, 2013).

Onshore and offshore hazardous liquid pipelines are regulated according to the Federal Regulation CFR Title 49, Part 195 entitled “Transportation of Hazardous Liquids by Pipeline”, which defines rules for system and incident reporting, design requirements, construction, pressure testing, operation and maintenance, and corrosion control. All parts of a pipeline facility through which a hazardous liquid or carbon dioxide moves in transportation, including, but not limited to, line pipe, valves, and other appurtenances connected to line pipe, pumping units, fabricated assemblies associated with pumping units, metering and delivery stations and fabricated assemblies therein, and breakout tanks are covered by the regulation.

The geographical coverage includes all 48 contiguous U.S. states, Alaska, Hawaii, offshore U.S. territories, and also the U.S. Outer Continental Shelf (OCS). As of 2012, the total pipeline network length covered by PHMSA is 299,674 km. Similar to CONCAWE, the pipelines are grouped according to the type of product transported, but the substance types are different. PHMSA substance types and corresponding total network lengths as of 2012 are given in Table 3.1.

Table 3.1. PHMSA pipeline substance types and corresponding network lengths

Substance Type	Network Length (km)
Crude oil	92,478
Petroleum/refined products which are liquid at ambient conditions	103,045
Highly volatile liquids (HVLs) or other flammable or toxic fluids which are gas as ambient conditions	96,337
Carbon dioxide (CO_2)	7,789
Biofuel/alternative fuel, including ethanol blends	26

A map of crude oil and refined product (HVL and non-HVL) pipelines including associated refineries in the U.S. is given in Figure 3.1.

Industries regulated by PHMSA are required to report loss of containment incidents which meet established reporting criteria. Although the rationale of the reporting criteria remained the same, the criteria themselves have changed several times since the publication of the related regulation in 1969 to keep them updated and also in some cases to make them more stringent. Current and previous reporting criteria for hazardous liquid transmission pipelines are summarised in Table 3.2.

The incident reports, which are publicly available on the PHMSA website, include information on the pipeline operator, location of the incident, operating conditions during and cause of the incident, physical damage to the pipeline and/or related equipment, type and amount of substance released, human health and environmental consequences, and emergency response/remediation activities.

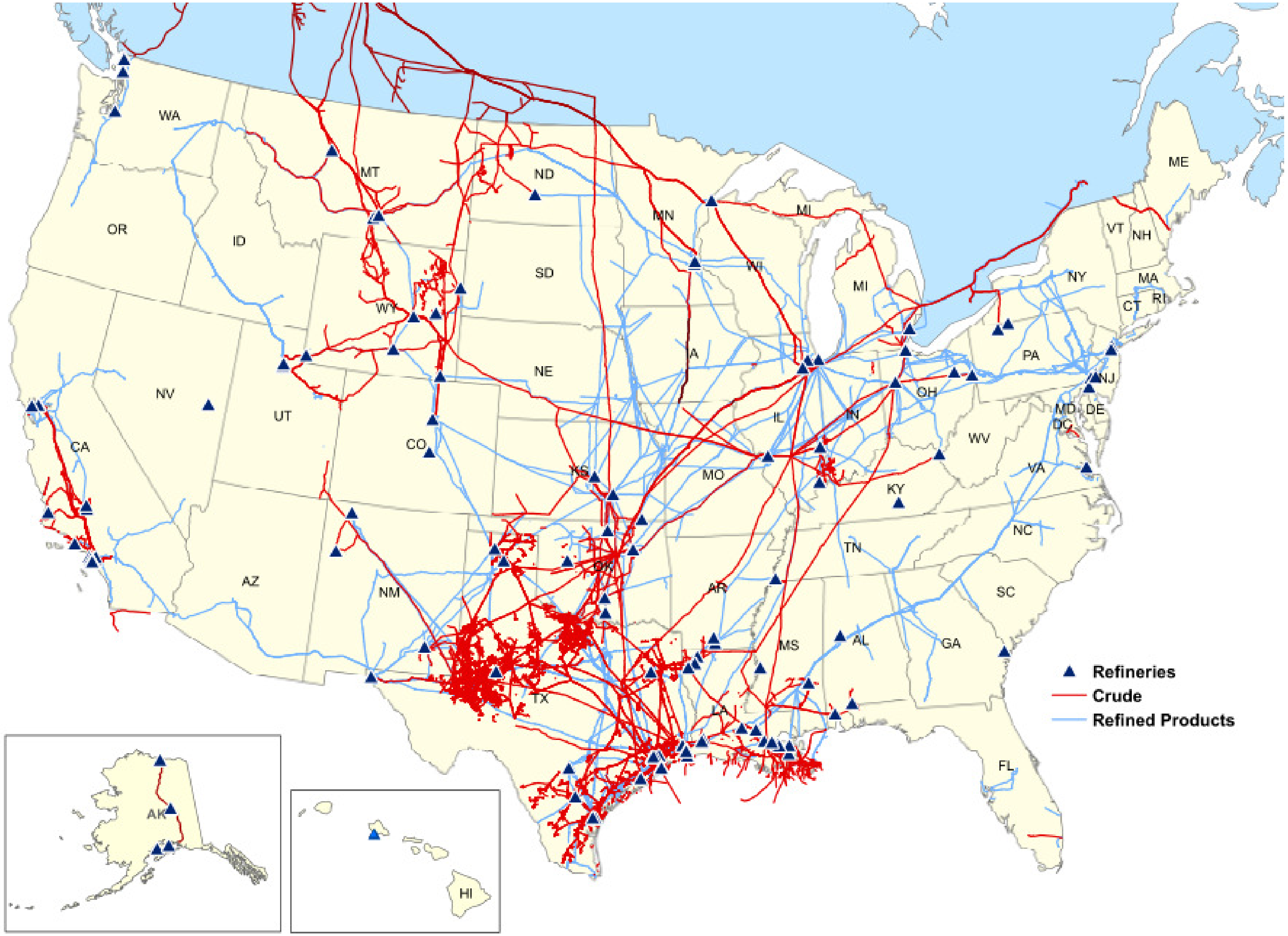


Figure 3.1. Map of the U.S. crude oil and refined product pipelines (API, 2013)

Table 3.2. PHMSA hazardous liquid incident reporting criteria

<table>
<tr><th>1969 (Original)</th><th>1979</th><th>1981</th><th>1991</th><th>1994</th><th>2002 (Current)</th></tr>
<tr><td>Explosion or fire not intentionally set the operator.</td><td>Same</td><td>Same</td><td>Same</td><td>Same</td><td>Explosion or fire not intentionally set the operator.</td></tr>
<tr><td>Loss of ≥ 50 BBL of liquid.</td><td>Same</td><td>Same</td><td>Loss of ≥ 50 BBL of hazardous liquid or CO_2.</td><td>Same</td><td rowspan="2">Release of ≥ 5 gal (19 L) hazardous liquid or CO_2 release, except ≤ 5 BBL (0.8 m^3) releases resulting from a pipeline maintenance activity if the release is:
• Not otherwise reportable,
• Not resulted in pollution of any stream, river, lake, reservoir, or other similar body of water that violated applicable water quality standards, caused a discoloration of the surface of the water or adjoining shoreline, or deposited a sludge or emulsion beneath the surface of the water or upon adjoining shorelines,
• Confined to company property or pipeline right-of-way,
• Cleaned up promptly.</td></tr>
<tr><td>Escape to the atmosphere of ≥ 5 BBL a day of liquefied petroleum gas of other liquefied gas.</td><td>Escape to the atmosphere of > 5 BBL a day of highly volatile liquids.</td><td></td><td>Same</td><td>Same</td></tr>
<tr><td>Death of any person.</td><td>Same</td><td>Same</td><td>Same</td><td>Same</td><td>Death of any person.</td></tr>
<tr><td>Bodily harm to any person resulting in one or more of the following:
• Loss of consciousness,
• Necessity to carry the person from the scene,
• Necessity for medical treatment,
• Disability which prevents the discharge of normal duties or the pursuit of normal activities beyond the day of the accident.</td><td>Same</td><td>Same</td><td>Same</td><td>Same</td><td>Personal injury necessitating hospitalization.</td></tr>
<tr><td>Property damage of ≥ 1,000 USD to other than operator's facilities, based upon actual cost or reliable estimates</td><td>Same</td><td>Estimated property damage to the property of the operator or others, or both, > 5,000 USD.</td><td>Same</td><td>Estimated property damage, including cost of clean-up and recovery, value of lost product, and damage to the property of the operator or others, or both, > 50,000 USD.</td><td>Estimated property damage, including cost of clean-up and recovery, value of lost product, and damage to the property of the operator or others, or both, > 50,000 USD.</td></tr>
</table>

The available PHMSA hazardous liquid incident reports for onshore and offshore pipelines cover a period of about 45 years starting from 1968. Partially in-line with the reporting criteria changes, the data is provided in 4 different data sets for the periods 1968-1985, 1986-2001, 2002-2009, and 2010 onwards. Because each data set has its own data format, various data extraction methods were applied to import the data into the study database as explained in the first year study report (Girgin and Krausmann, 2014a). Using recently published, updated versions of the source datasets (PHMSA, 2014a), the total number of incidents, which was reported as 11,246 in the first year final report, has increased to 12,515 by inclusion of previously missing incidents that occurred in 2009. Similar to the previous incident records, newly added incident records were also classified by the keyword based automated classification followed by manual peer-review.

Although the PHMSA incident data is present starting from 1968, the available data is not sufficient to distinguish natech incidents until 1986. For this period, cause descriptions do not include natural hazards and narratives giving insight into the incidents also do not exist. For selected cases was is possible to identify natechs using information provided by external references and cross checking with disaster records, such as FEMA disaster declarations or NOAA severe weather records. However, a classification of all natechs was not possible. Consequently, the study only covers incidents that occurred in the period 1986-2012, thereby excluding 4,727 incidents that happened before 1986. For the study period of 27 years, there are 6,976 reported onshore incidents (Figure 3.2).

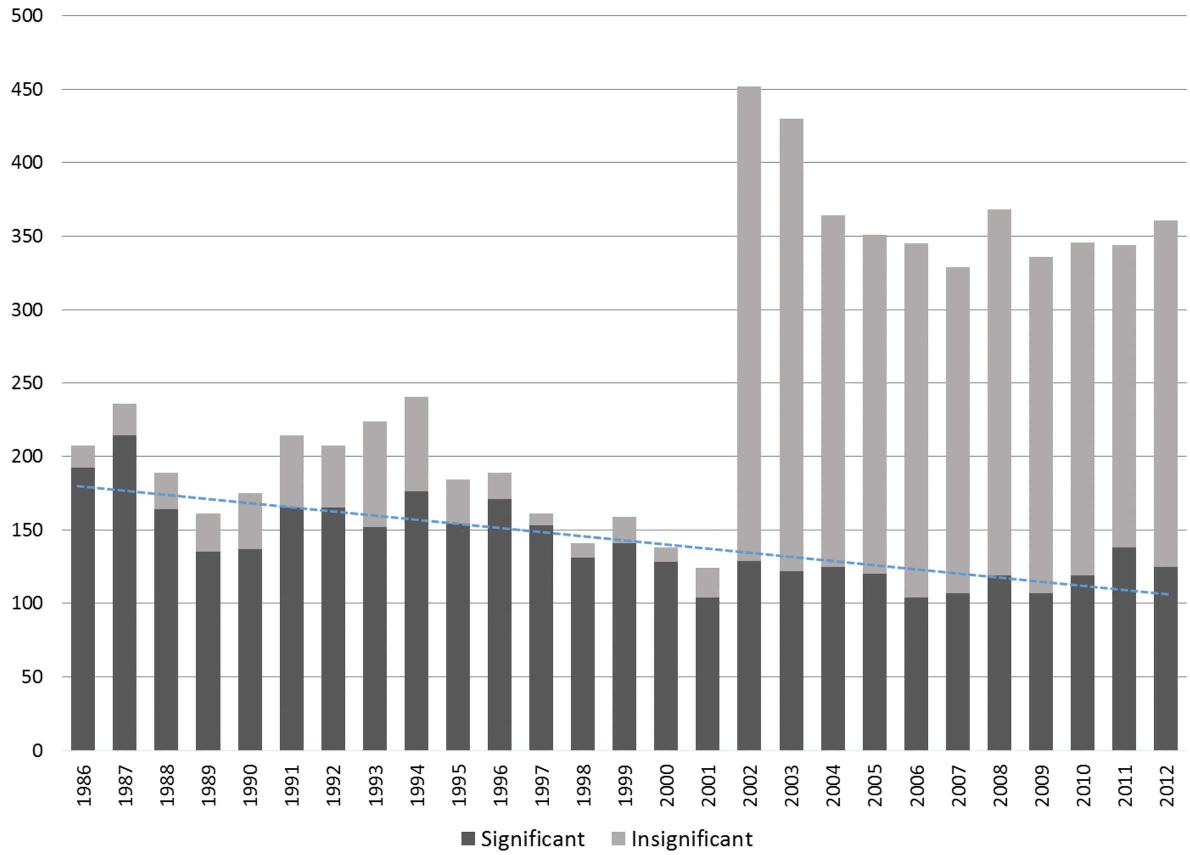


Figure 3.2. Yearly distribution of significant and non-significant PHMSA incidents (blue = trend line)

Figure 3.2 shows that the incident data is not uniform. As summarized in Table 3.2, within the study period, the reporting criteria changed three times. In 1991, CO_2 was included in the list of hazardous substances. In 1994, the cost criterion for reporting estimated property damage to the operator or others was increased from 5,000 USD to 50,000 USD including clean-up, recovery and product loss costs. Lastly, in 2002, the minimum reporting quantity was decreased to 5 gallons with special exemption conditions for spills < 5 BBLs. Additionally, the reporting data format was also altered twice (in 2002 and 2010). The yearly time series of the incidents clearly shows the effect of the more stringent reporting criteria put into force in 2002, which increased the number of reported incidents significantly about 3 fold (Figure 3.2). The change in the reporting data format in 2010 did not result in a similar variation as both the old and new reporting formats were detailed and similar in extent, unlike the previous format which was considerably different and less comprehensive.

In order to eliminate the effect of changing reporting criteria, PHMSA categorizes incidents as significant and non-significant by using the following standardized criteria for significant incidents:

- Explosion or fire not intentionally set by the operator
- Death or personal injury requiring hospitalization
- ≥ 50,000 USD estimated total costs, measured in 1984 USD
- ≥ 5 BBL Highly Volatile Liquid (HVL) release
- ≥ 50 BBL non-HVL release

When non-significant incidents are filtered out, a continuous trend is obtained for the remaining incidents as shown in Figure 3.2, which can be used for long-term statistical analysis. Therefore these criteria are utilized for this study to obtain a consistent data set. An overall decreasing trend is observable in the occurrence of significant incidents from all causes.

Among the incidents that occurred in 1986-2012, 387 incidents (5.5%) were found to be natech events (Figure 3.3). In the original data set, only 63% of these incidents were indicated as natural hazard related. The remaining natechs were identified by the automated classification and peer review of the incidents. This indicates that the existing PHSMA incident cause descriptions do not fully represent the actual causes, resulting in an underestimation of natech incidents. 75% of the natechs identified during manual review are from the 1986-2001 period. Therefore, the inaccuracy is higher in the early data sets and decreases in the later ones.

Although the effect is not as pronounced as for all incidents, the time series of unfiltered natech incidents also shows an increasing trend after 2002 (Figure 3.3). However, once the effect of non-significant incidents is eliminated, the distribution of significant natechs does not have a statistically significant trend. Only some isolated years are found to have more natech incidents than the others. In general, it can be concluded that the number of natech occurrences does not seem to increase.

However, if the yearly trend of the ratio of the significant natechs to the significant incidents from all causes given in Figure 3.4 is examined, a rise is observable in the last decade. As can be seen more clearly from the 3-yearly moving average trend line, the ratio of natechs is increasing within the incidents. Taking the overall decreasing trend of the significant incidents and stable trend of the natechs into consideration, this increase can be attributed to a decrease in other types of incidents. As design standards, construction quality and operating practices of pipelines improve, incidents due to natural hazards become more important as a consequence.

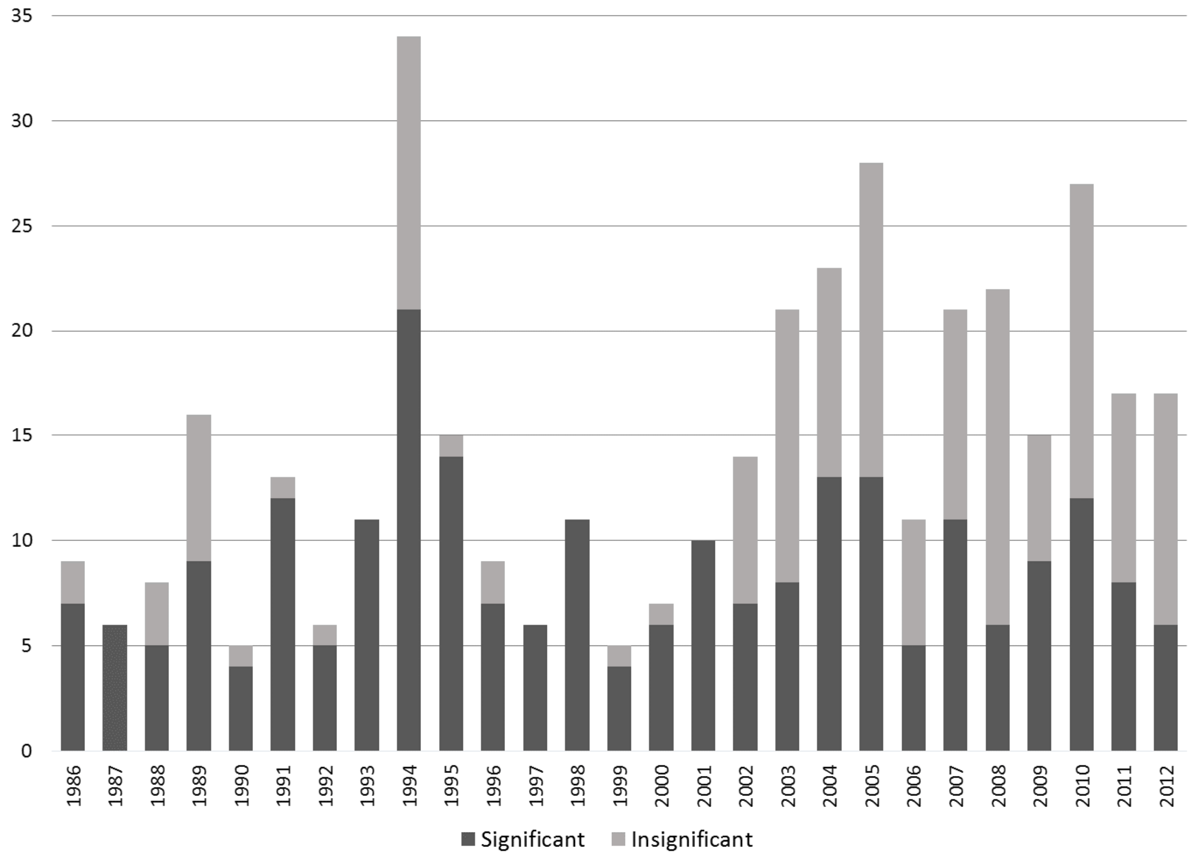


Figure 3.3. Yearly distribution of significant and non-significant PHMSA natech incidents

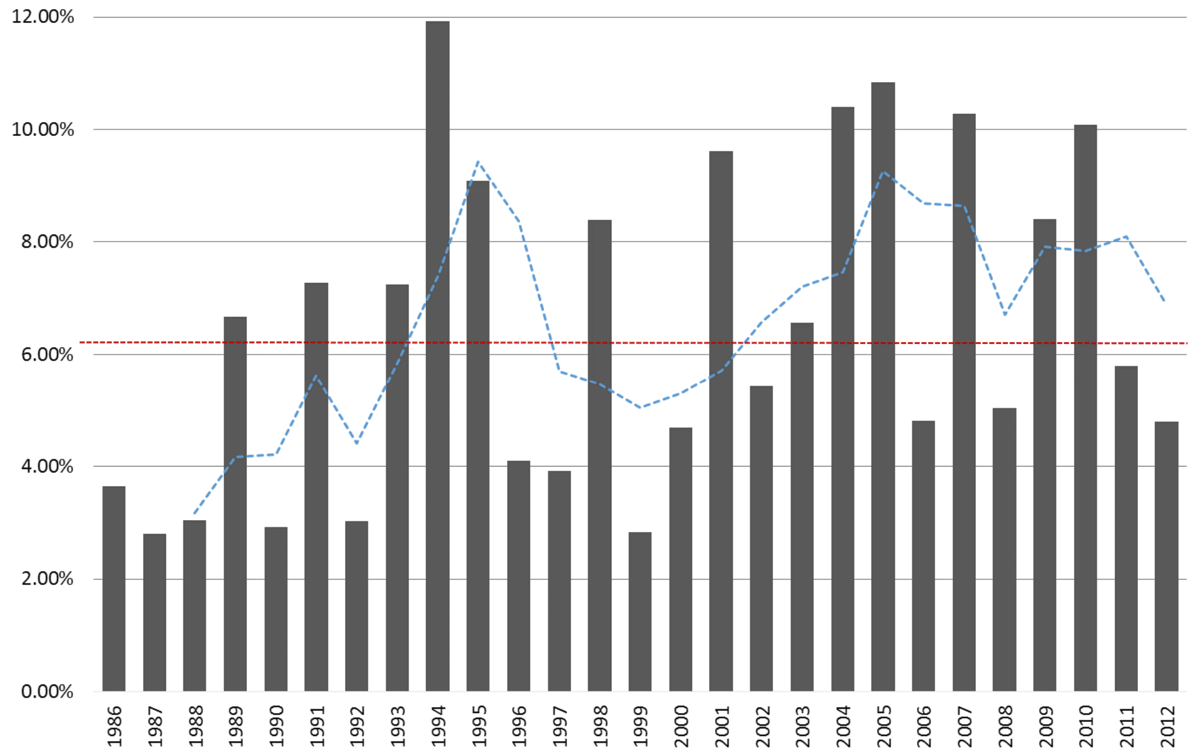


Figure 3.4. Yearly ratio of significant natechs to significant incidents (red = average, blue = moving average)

Also as shown in Figure 3.5, for the last decade, the yearly average of the ratio of the number of significant natechs to the number of all natechs is considerably larger than the ratio of the incidents. This suggests that natech incidents tend to be more severe events in terms of consequences than other incidents not triggered by natural hazards.

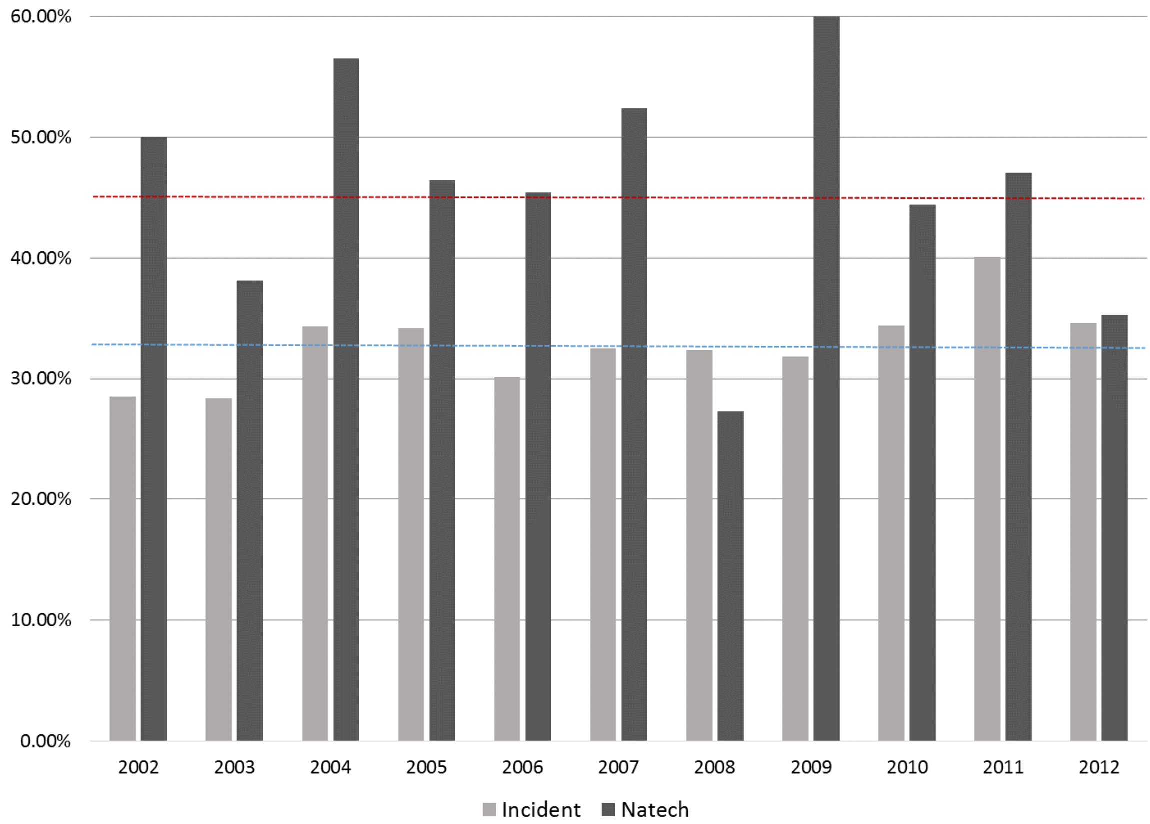


Figure 3.5. Yearly ratio of significant natechs and incidents to all natechs and incidents (blue - red = average)

Data collected for the period 2002-2012 allows the assessment of the status and contribution of non-significant natechs. In this period, there were 98 significant and 118 non-significant natechs, which correspond to 45% and 55% of the natech incidents, respectively (Figure 3.3). Although their total number is higher, a preliminary analysis showed that all non-significant natechs together correspond to less than one percent of the significant incidents in terms of the quantity of substance released (0.6%) and the total cost of damage (0.1%). In fact, the *total* quantity of released substance (604 BBL) and the *total* cost of damage (2.3 million USD) of non-significant natechs are less than the *average* values of the significant natechs (1,087 BBL and 2.4 million USD). Therefore, a detailed analysis of the consequences of natechs was carried out only for the significant incidents. Only in certain instances reference is made to the non-significant natechs for comparison purposes.

Among the natechs marked as not significant by the PHMSA in 1986-1994, 3 additional natechs were found to be fulfilling the significance criteria according to the incident narratives and they were included in the analysis as significant natechs. In 1994-2012, all non-significant natechs were properly indicated in the original data set. It should be noted that the actual number of reported significant incidents and also natechs could be higher due to under-reported release quantities and economic cost estimates as illustrated by the examples given in the following subsections. However, for the current analysis this is not taken into consideration and values as published by PHMSA are used unless otherwise stated.

3.1. Descriptions of Natech Incidents

In order to understand the natural hazard impacts, natech failure modes, and their consequences, the PHMSA natech incidents were studied individually. In addition to the original PHMSA data, related information available in the study database (e.g. NRC reports, FEMA disaster declarations, NOAA storm records) was evaluated. Supplementary information from scientific publications, technical reports, newspaper articles, and online resources was also collected.

Aggregated information for each natech incident can be accessed in a structured manner from the related incident information page available in the data analysis system. An example information page is shown in Figure 3.6.

The available data for each natech incident includes:

- Date and time of the incident
- Incident location (U.S. state, county, geographic coordinate, and address description)
- Operator information
- Pipeline characteristics (e.g. diameter, material, installation year)
- Pipeline system part and item involved
- Item location
- Substance involved
- Type of natural hazard and related disaster record (if available)
- Incident narrative
- Natural hazard impact and damage modes
- Amount of released and recovered material
- Release medium
- Total economic cost (reported and current as adjusted for inflation)
- Number of fatalities and injured people
- Fire and explosion indicators
- Data uncertainty indicators
- Significance indicator
- Related NRC incident reports
- Research notes including information from other resources and references
- Data analysis tags

Summary data on the analysed PHMSA data is provided in Appendix B for each incident including date, county, substance involved, system part, system item, item location, pipe diameter, natural hazard impact and damage modes, release medium, amount of spill, total economic cost (as adjusted for inflation), and fire indicator. Short descriptions of the incidents can also be found in the previous intermediate report (Girgin and Krausmann, 2014b).

JOINT RESEARCH CENTRE

Natech Incident Data Analysis Tools

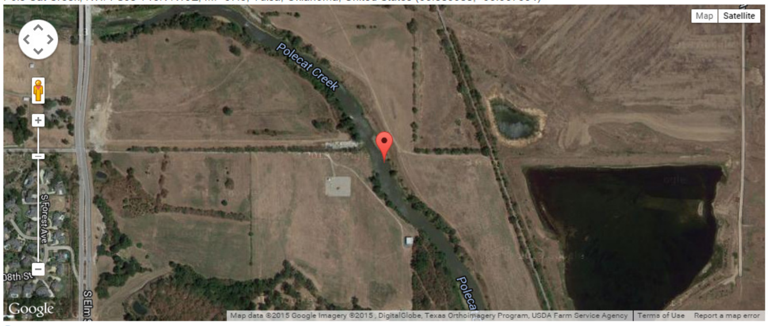
European Commission > JRC > IPSC > Natech Incident Data Analysis Tools

Incident Significant

Source
PHMSA Hazardous Liquid Incident Data 19980161

Date
1998/10/07 03:15

Location
Pole Cat Creek, NW/4 S30 T18N R13E, MP 87.3, Tulsa, Oklahoma, United States (36.009900, -95.967664)



Map

Activity
Transport via pipeline (H49.50)

Operator
Conoco

Incident Type
Pipeline Natech

Event Description
Failure due to excessive external forces by the flood waters and debris impact upon the pipeline after the erosional forces of the water exposed it.

System Characteristics
Pipeline, Pipe, 10.00", 1970 (Underground)

Natural Hazard
Flood (Riverine flooding): Flood, 98/10/05 - 98/10/06, Oklahoma, United States

Damage
Rupture (Pipe failure) – Flood waters > Washout > Debris impact > Pipe failure

Substance
Propane, Released: 1,500 barrels

Medium
Stream, Pole Cat Creek

Consequences
Total Cost: 200,000 USD (272,400 USD in 2013 based on GDP-2010)

Description
On October 6, 1998, Conoco Pipeline (CPL) oil movements group located in Houston, Texas, received a deviation alarm on its SCADA system. The alarm indicated a pressure deviation on the No. 2 Glenpool, Oklahoma to Wood River, Illinois, 10" pipeline, near Glenpool Station. Upon receiving the alarm, oil movements initiated emergency shut down procedures for the system, which includes line isolation by remotely operated block valve. During the shutdown procedure emergency response personnel were notified of the possibility of a release and dispatched to the suspect location. Response personnel began systematic search for the actual release location by closing manually operated block valves and walking the pipeline. After several sweeps of the suspect line segment, detection equipment continually picked up faint signals that indicated the presence of a hydrocarbon around the Pole Cat Creek subsurface line crossing. At presence of a hydrocarbon around the Pole Cat Creek subsurface line crossing. At 6:03 a.m. emergency response personnel confirmed the release location as the Pole Cat Creek crossing. This was evidenced by occasional bubbles on the water surface near the approximate location of the pipeline crossing. This determination was difficult as the creek was above flood stage and the water extremely fast and turbulent, due to recent torrential rains in the area. The failure location was further confirmed by displacing the line with nitrogen and watching for additional bubbles. The failure was displacing the line with nitrogen and watching for additional bubbles. The failure was determined to be the result of excessive external forces brought about the flood waters and debris impact upon pipeline after the erosional forces of the water exposed it. To prevent future occurrences of this type of failure, the crossing was replaced by directionally drilling and installing new pipe 30 feet below the fluidized bed of the creek.

Search

Notes
Mentioned in "Report to Congress: Results of Hazardous Liquid Incidents at Certain Inland Water Crossings Study":

Conoco reported a 1,500-barrel propane spill in Pole Cat Creek in Oklahoma occuring on October 7, 1998. The 10-inch diameter pipeline failed after soil eroded from around the pipeline and debris struck the pipeline. (PHMSA, 2012, p. 8)

NCDC records (Natural Disaster 367649, Natural Disaster 367039) indicate flooding in Tulsa area (Pole Cat Creek) one day before the incident.

Natural force damage | Excessive external force | Debris impact | Stream erosion | Important | Water crossing | Township coordinate | Approximate coordinate | PHMSA crossings study

Related Incident Reports

No	Date	Country	Incident	Description	Source
1. 368242	98/10/07	OK	Pipeline Natech Flood Flood, 98/10/05 - 98/10/06 98/10/07, OK, Pipeline Natech	10" Interstate Pipeline Cause: Unknown Release Duration: 30 min Fire involved: No Reached water: Yes Isolated the pipeline Conoco Pipeline Norhtwest Quarter of Section 30, Tulsa (Broken Arrow), Tulsa Atmosphere (Air) Propane	

This record is last **reviewed** on 2013/06/04 14:09 by Serkan Girgin, **reviewed** on 2014/01/06 09:56 by Serkan Girgin [*]. [3 actions]

Edit | 8349 | Source Data

Figure 3.6. Sample incident information page

3.2. Analysis of Natech Incidents

The yearly time series of the pipeline natech incidents shows a fluctuating trend with local peaks for certain years, e.g. 1994 and 2005. As discussed in the failure modes section, these years are known to have had major natural disasters resulting in significant technological and industrial damage besides damage to public assets. In 1994, the Northridge Earthquake (M 6.7) in California cracked welds at several locations along a 10-inch pipeline transporting crude oil from the San Joaquin Valley, resulting in an extensive oil spill along the Santa Clara River (Leveille et al., 1995). Again in 1994, the San Jacinto River flood in Texas released more than 35,000 barrels of petroleum and petroleum products into the river from 8 pipelines that ruptured, and 29 pipelines were undermined both at the river crossing and new channels formed in the flood plain. Ignition of the released products within the flooded residential areas resulted in burn and inhalation injuries (NTSB, 1996a). In 2005, Hurricanes Katrina and Rita resulted in substantial damage in the southern coastal areas of the U.S including onshore and offshore pipeline systems (Cruz and Krausmann, 2009). Although not as significant as these years, there are also other years with a high number of natech incidents. A comparatively higher number of incidents are observed in the second half of the series.

Natural Hazards

The overall distribution of significant natechs in 1986-2012 with respect to natural hazards is illustrated in Figure 3.7. The main natural hazard category triggering natechs is meteorological hazards. 37% of the natechs appears to be due to the hazards in this category. Geological hazards are the second most important category with 27%, followed by climatic and hydrological hazards with 23% and 13%, respectively. The uncertainty in the incident classification with respect to natural hazards is estimated as 5%.

Within geological hazards, subsidence is the major hazard with 34% contribution, followed by frost heave with 27%. Incidents caused by rocks resting on pipelines and resulting in dent cracks are found to be significant and are more frequent than landslides. Although considered as a major geological hazard for pipelines, there are only 6 incidents (9%) triggered by earthquakes and all of them were due to a single event (Northridge Earthquake, MW 6.7, January 17, 1994).

Among meteorological hazards, lightning caused the highest number of incidents with 60% of the incidents in this category. 19% of the incidents were due to heavy rainfall, followed by storms and tropical cyclones with 7% contribution each. High winds, tornados, and winter storms have the lowest number of incidents.

As for hydrological hazards, approximately 80% of the incidents are due to flooding and the remainder is related with stream erosion/scouring during normal flow conditions. It should be noted that based on the available data it was not always possible to differentiate washouts during normal flow conditions from those during flooding conditions. Therefore, the actual distribution can be slightly different although the number of natechs under hydrological hazards stays the same.

Within climatic hazards, freezing is the major hazard with 73% of the incidents followed by cold weather which is 18%. Overall, cold weather-related hazards make up more than 90% of the natechs triggered by adverse climatic conditions. The remainder was due to hot weather and droughts.

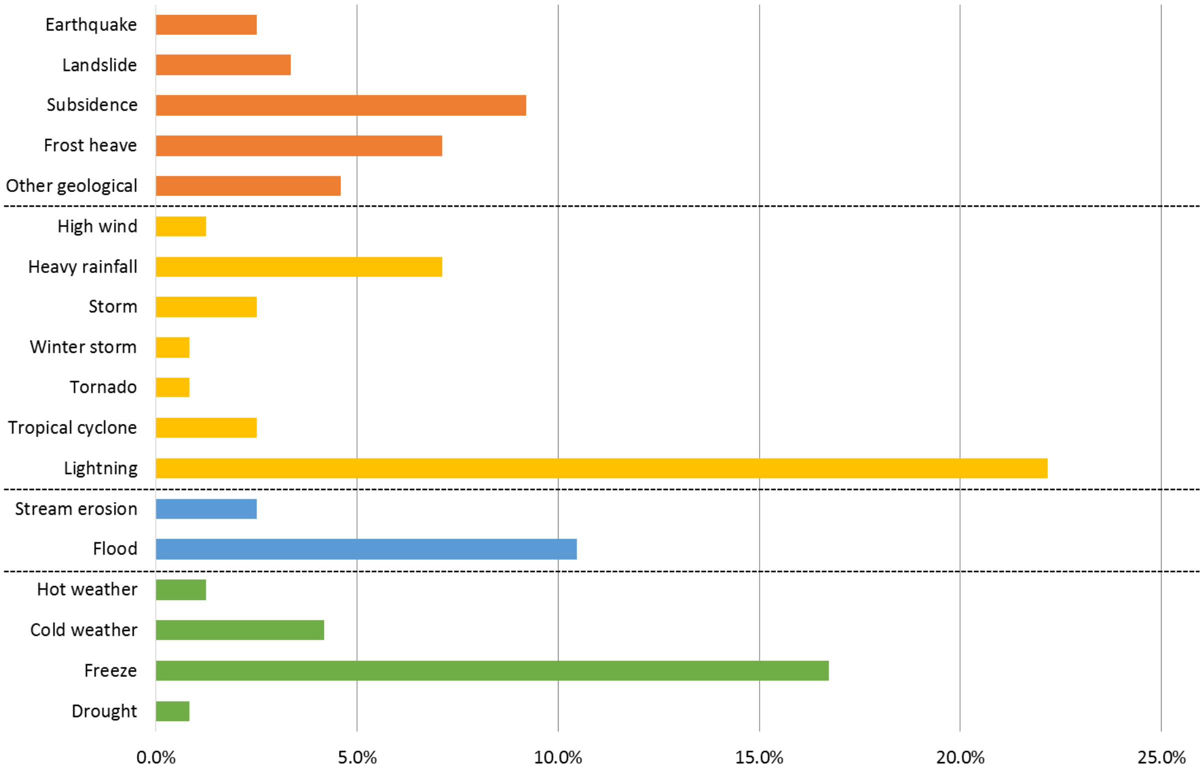


Figure 3.7. Distribution of the number of significant incidents with respect to natural hazards

System Parts

In order to analyse the vulnerability of the different parts of the onshore hazardous liquid pipeline systems, the natechs were categorized under the following system parts:

- Pipeline: Line pipe including valve sites
- Aboveground storage: Breakout tanks or storage vessels including attached appurtenances
- Belowground storage: Equipment and piping associated with belowground storage
- Station: Equipment and piping associated with pump/meter station, except storage units
- Terminal: Equipment and piping associated with terminal/tank farm, except storage units

Whenever available, the original PHMSA data fields were used to classify the incidents with respect to system parts. Because the system part classification used for the incident reports was not consistent throughout the study period, some incidents were manually classified by using the location and event narrative information. Cross-checks were carried out by using high-resolution satellite imagery. In some cases it was not possible to differentiate stations and terminals. However, aboveground storage incidents are clearly separated from the station and terminal incidents.

The final classification shows that almost half of the significant natech incidents occurred at pipelines (Figure 3.8). Aboveground storage incidents correspond to about one third of all natechs, followed by stations and terminals. Only one significant belowground storage natech was identified, which is not considered for further analysis. The distribution of natechs with respect to system part differs for significant and non-significant incidents. For the period 2002-2012, significant natechs seem to occur more frequently at pipelines and aboveground storage compared to stations and terminal. In contrast, non-significant natechs often took place at terminals and stations instead of aboveground storage units and pipelines (Figure 3.9).

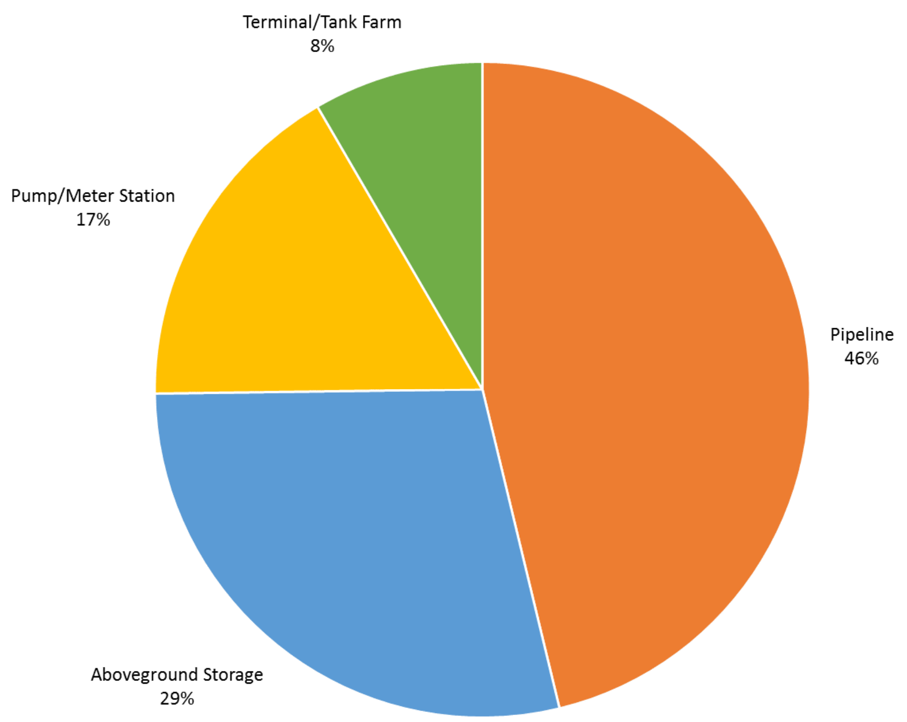


Figure 3.8. Distribution of significant natechs with respect to system parts

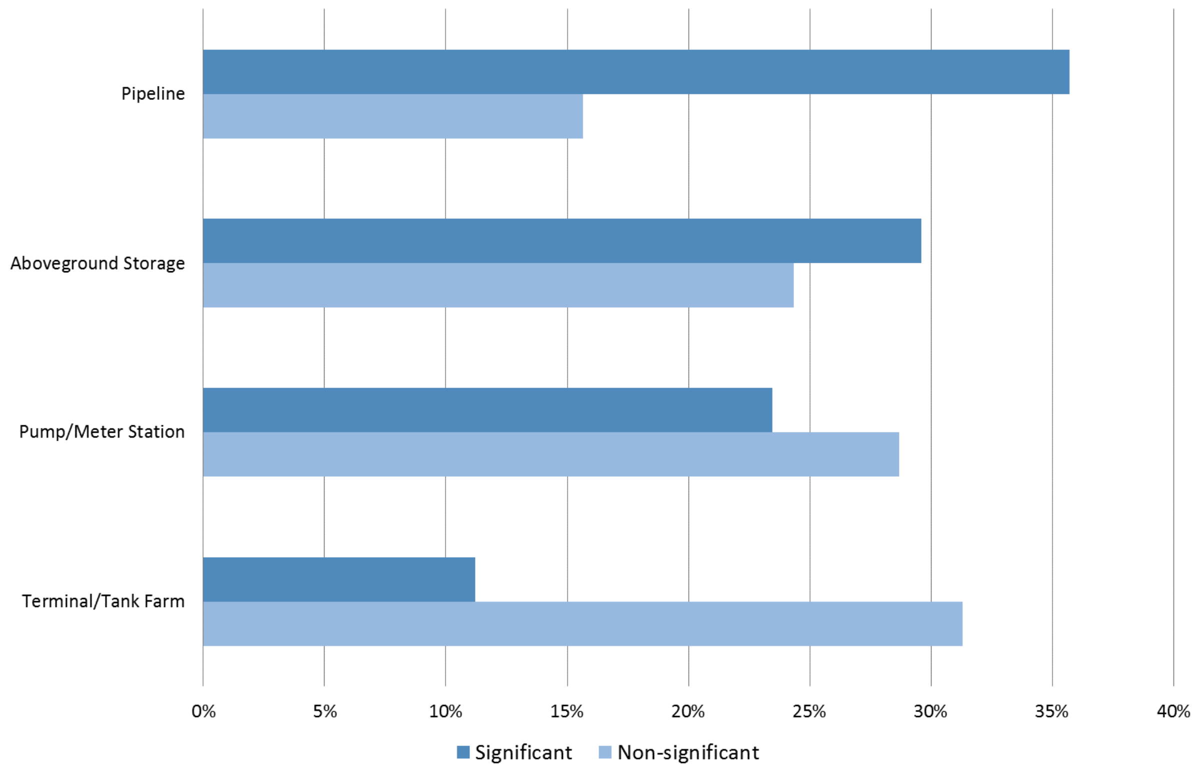


Figure 3.9. Distribution of significant and non-significant natechs with respect to system part

The distribution of the number of natech incidents with respect to system part is highly natural hazard dependent (Figure 3.10). The proportion of pipeline incidents is significant in case of geological and especially hydrological hazards, whereas it is much less for meteorological and climatic hazards. For geological hazards, natechs involving aboveground storage units and terminals were only around 5%. Terminals and stations contributed even less for hydrological hazards. For meteorological and climatic hazards, aboveground storage units were the most important system part with more than 40% of natechs by number. Natechs at stations had 20% contribution for both categories, whereas the lowest contribution was from terminals.

From the system part point of view, aboveground storage units were mostly affected by meteorological and climatic hazards (Figure 3.11). Hydrological hazards did not seem to affect this part of the pipeline systems. Likewise, geological hazards were also comparatively insignificant. Although the percentages change slightly, stations and terminals showed a similar pattern with respect to the overall distribution of the natural hazards. For these system parts, the involvement of geological hazards were around 20%, and the contribution of hydrological hazards was less than 5%. Climatic hazards were relatively more frequent for the terminals compared to the stations, resulting in less contribution from meteorological events. For pipelines, geological hazards were the primary trigger with approximately 45%, followed by hydrological hazards and meteorological hazards. Climatic hazards contributed in a lesser extent. Natechs due to drought, stream erosion/scouring, flooding, resting rock, landslide, and earthquake hazards were observed only at pipelines. Subsidence events also mostly affected the pipelines, although a small number of related incidents occurred at other system parts. Incidents at pipelines were also significant in cold weather and frost heave natechs. The vast majority of the heavy rainfall natechs hit aboveground units. Aboveground storage incidents were also the highest for freeze and lightning.

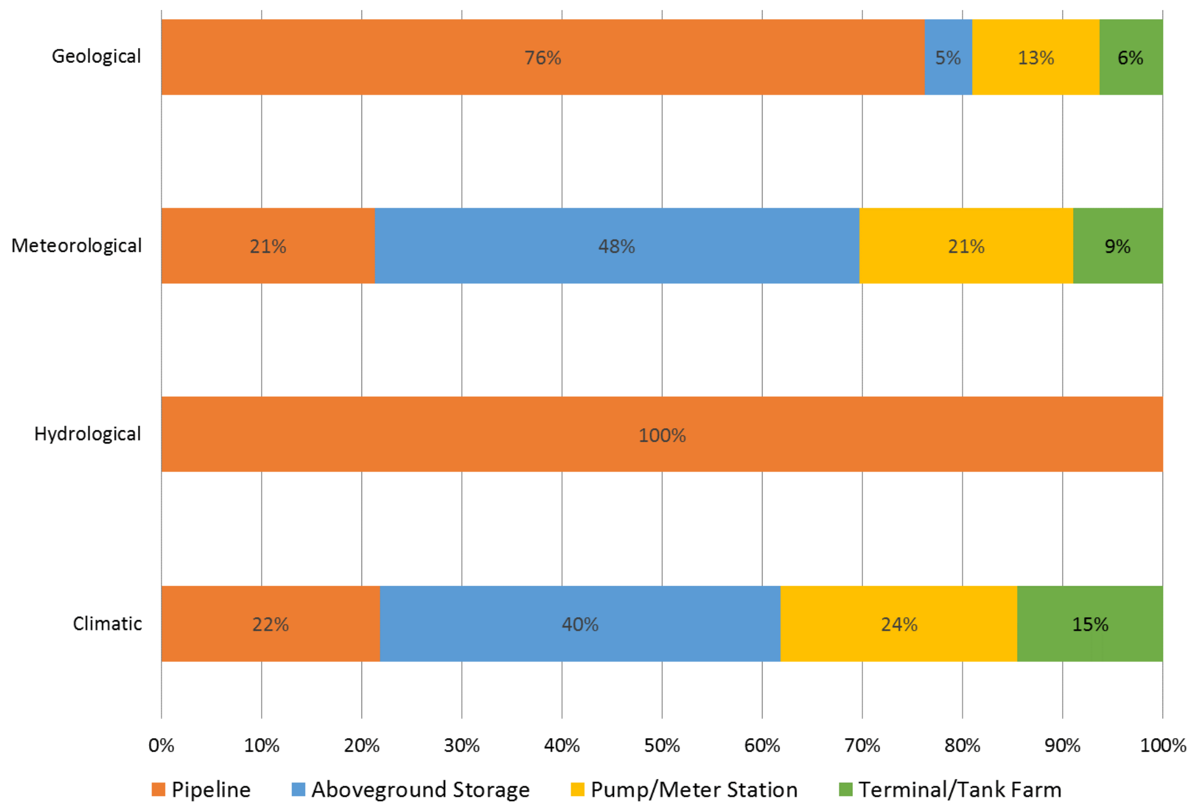


Figure 3.10. Distribution of system parts of significant natechs with respect to hazard categories

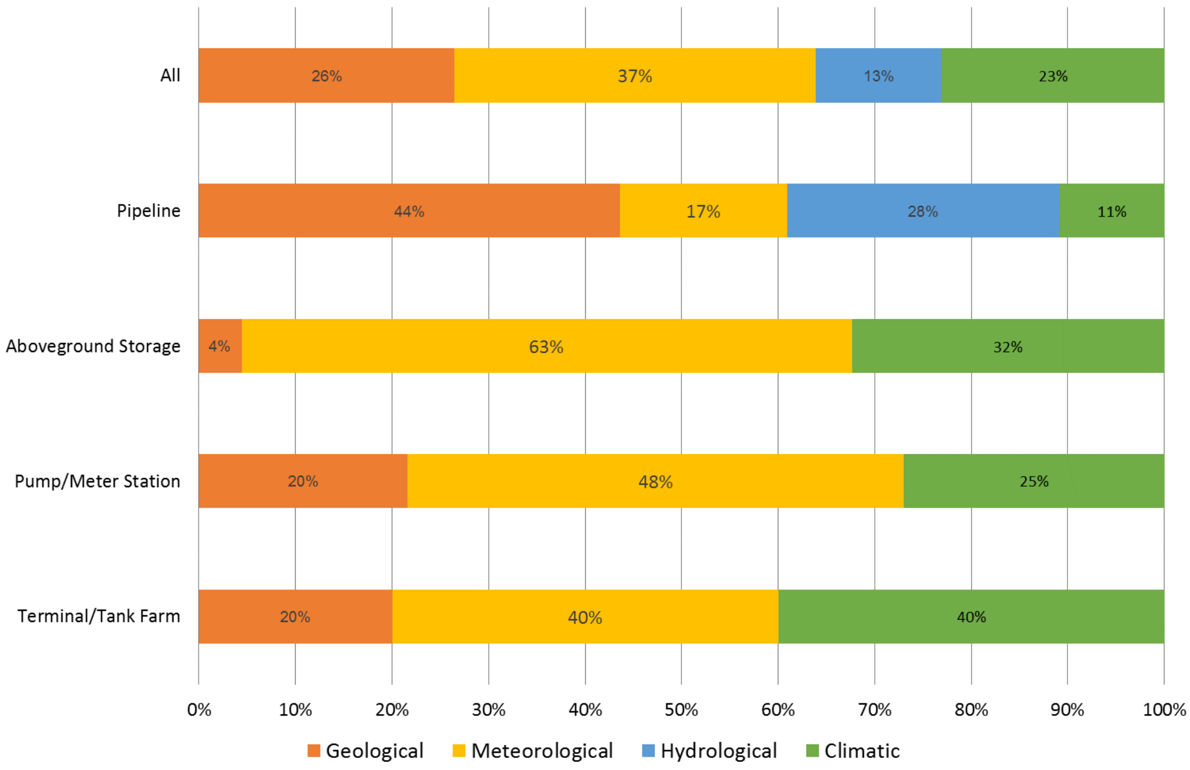


Figure 3.11. Distribution of hazard categories of natechs with respect to system parts

Release Quantities

In the study period (1986-2012), natechs resulted in approximately 320,000 BBL of hazardous materials releases. For the same period, the total release due to pipeline incidents from all causes was 3,740,000 BBL. Therefore, the natech contribution is around 8.5%.

The distribution of yearly total release amounts shows that for the majority of years the total release amount was less than 10,000 BBL for natechs. There are only 4 years having a total release greater than 30,000 BBL, which are 1987, 1994, 2001, and 2005 (Figure 3.12). For all these years except 1987, natechs constituted more than 30% by volume of all the accidental releases that occurred in that year (Figure 3.13). The high amount of release in 1987 is mainly due to a severe flooding event in Oklahoma that resulted in a major crude oil release from a pipeline on May 30, 1987 at a newly formed channel of the Red River near Cotton (Incident #19870131).

The total release amount of the analysed natech incidents is summarised in Table 3.3. The distribution of natechs with respect to hazard categories based on total release quantities shows that geological, meteorological and hydrological hazards had almost equal contributions with approximately 30% each (91,300 – 102,900 BBL) (Figure 3.14). Climatic hazards had a share of only 8%. The natural hazard resulting in the highest amount of release was flooding with 95,000 BBL (30%), followed by tropical cyclones, with about 56,800 BBL release. Within geological hazards, frost heave (41,500 BBL) and subsidence (34,000 BBL) were the most significant hazards. They were also third and fourth most significant overall. Because of the low number of occurrence (≤ 3), high wind, winter storm, tornado, hot weather and drought incidents resulted in insignificant amounts of releases.

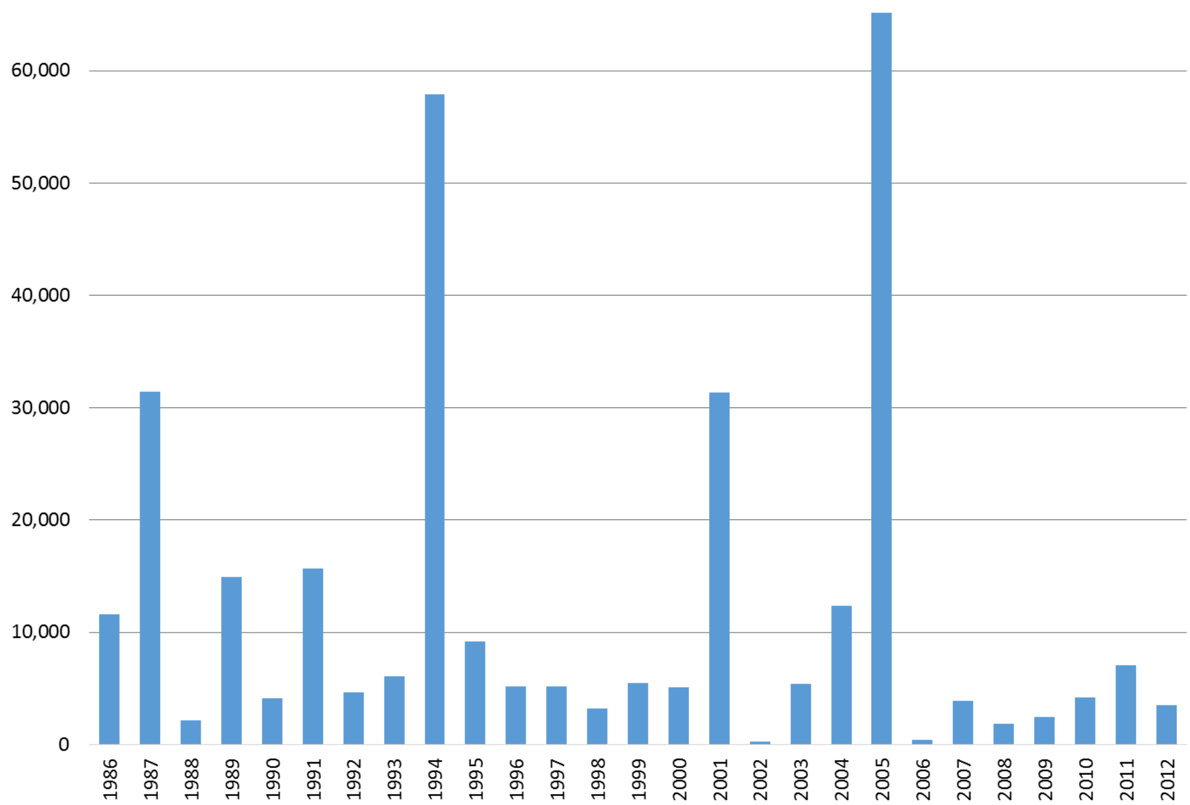


Figure 3.12. Yearly distribution of the total amount of substance release of the significant natechs

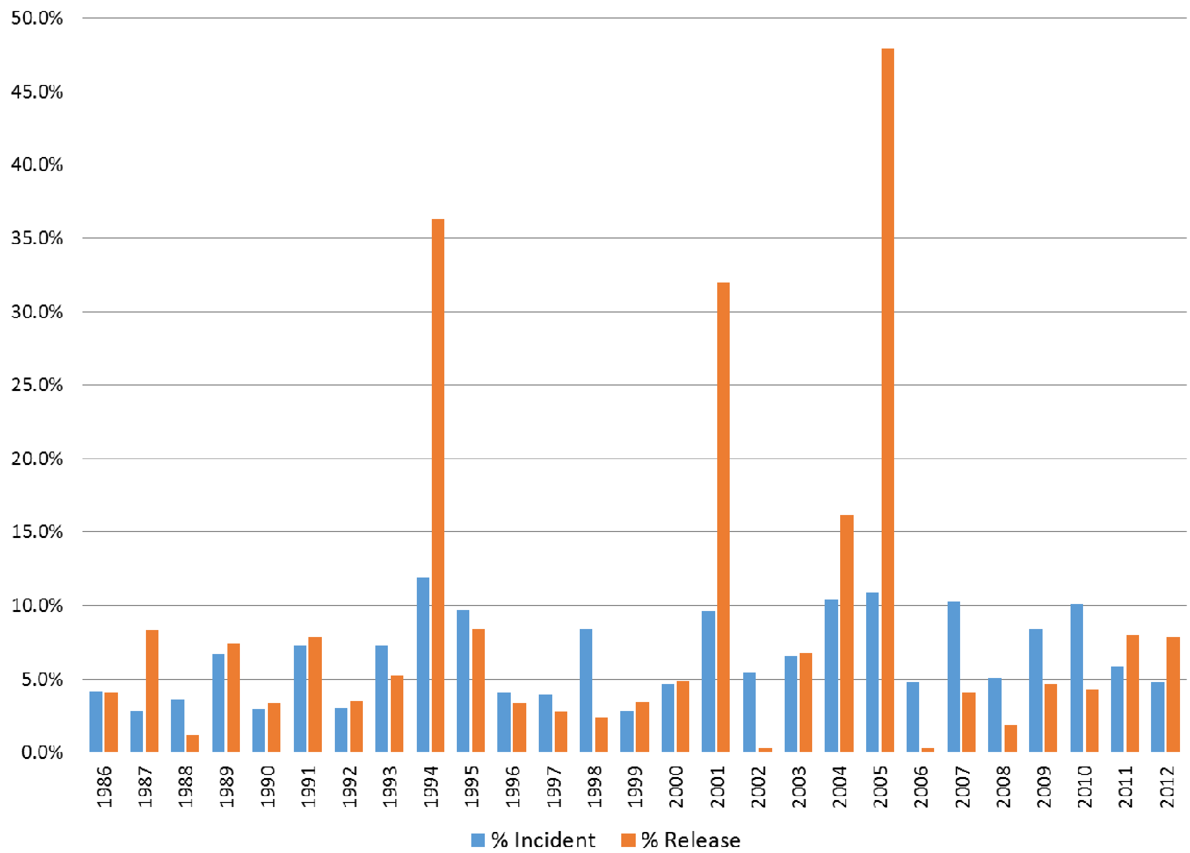


Figure 3.13. Percentage of natechs with respect to the number of incidents and total amount of spill

Table 3.3. Total release amount of significant natech incident by natural hazard and system part

Natural Hazard	Pipeline	Aboveground Storage	Pump/Meter Station	Terminal/ Tank Farm	Total
Geological	*94,749*	*1,985*	*1,617*	*134*	*98,485*
Earthquake	6,139	-	-	-	6,139
Landslide	10,177	-	-	-	10,177
Subsidence	33,688	60	192	3	33,943
Frost heave	37,965	1,925	1,425	131	41,446
Other geological	6,780	-	-	-	6,780
Meteorological	*11,770*	*69,743*	*8,083*	*1,692*	*91,288*
High wind	404		56	176	636
Heavy rainfall	-	10,322	72	55	10,449
Storm	-	400	136	20	556
Winter storm	-	475	-	115	590
Tornado	-	215	33	-	248
Tropical cyclone	3,245	52,197	-	1,326	56,768
Lightning	8,121	6,134	7,786	< 1	22,041
Hydrological	*102,899*	-	-	-	*102,899*
Stream erosion	7,921	-	-	-	7,921
Flood	94,978	-	-	-	94,978
Climatic	*9,000*	*12,927*	*3,109*	*2,080*	*27,116*
Hot weather	-	-	411	-	411
Cold weather	7,147	1,893	110	-	9,150
Freeze	1,453	11,034	2,588	2,080	17,155
Drought	400	-	-	-	400
TOTAL	218,418	84,655	12,809	3,906	319,788

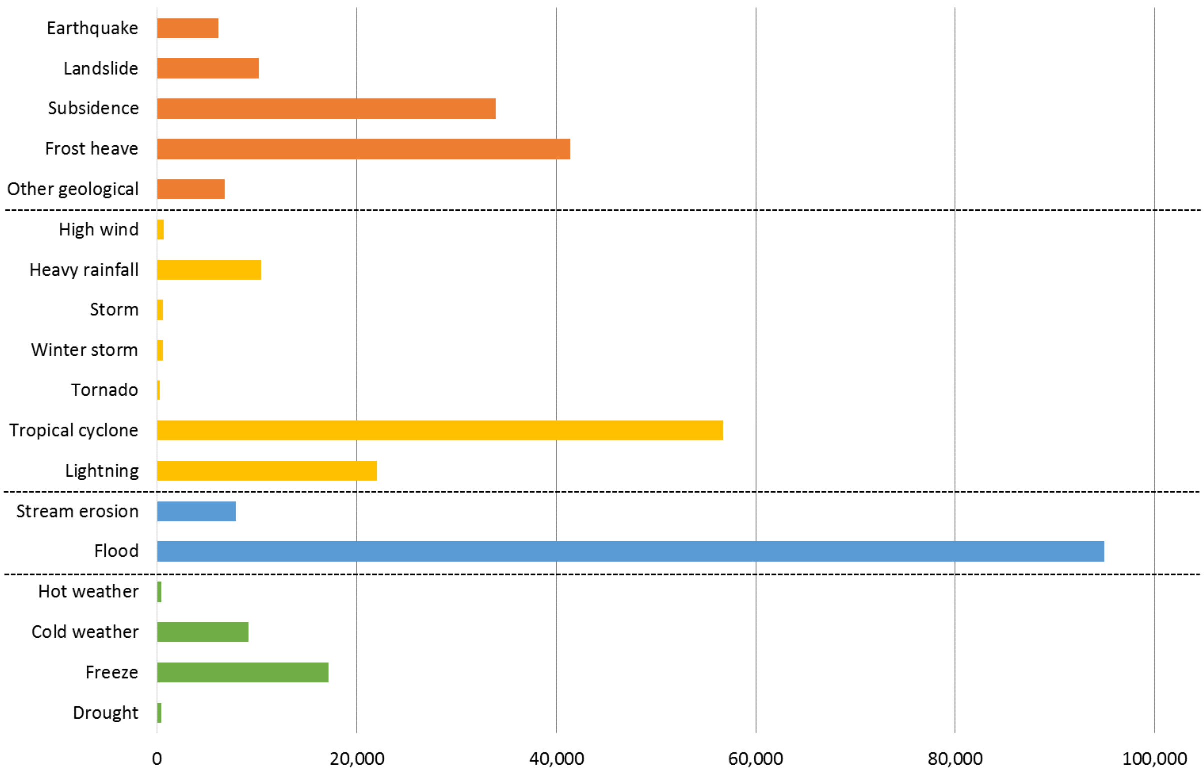


Figure 3.14. Distribution of the release quantities of significant natechs with respect to natural hazards

In line with the number of incidents, all of the releases due to hydrological hazards were from pipelines (Figure 3.15). Although in terms of incident occurrence the contribution is slightly lower (76%), almost all of the geological hazard-related releases were also from the pipelines. Meteorological hazards resulted in the highest amount of release at aboveground storage units. Releases from pipelines and stations were less significant for this hazard category. Aboveground storage units also had the highest contribution in climatic natechs corresponding half of the total releases, followed by pipelines with a one third contribution. Releases from stations and terminals were minor for climatic hazards.

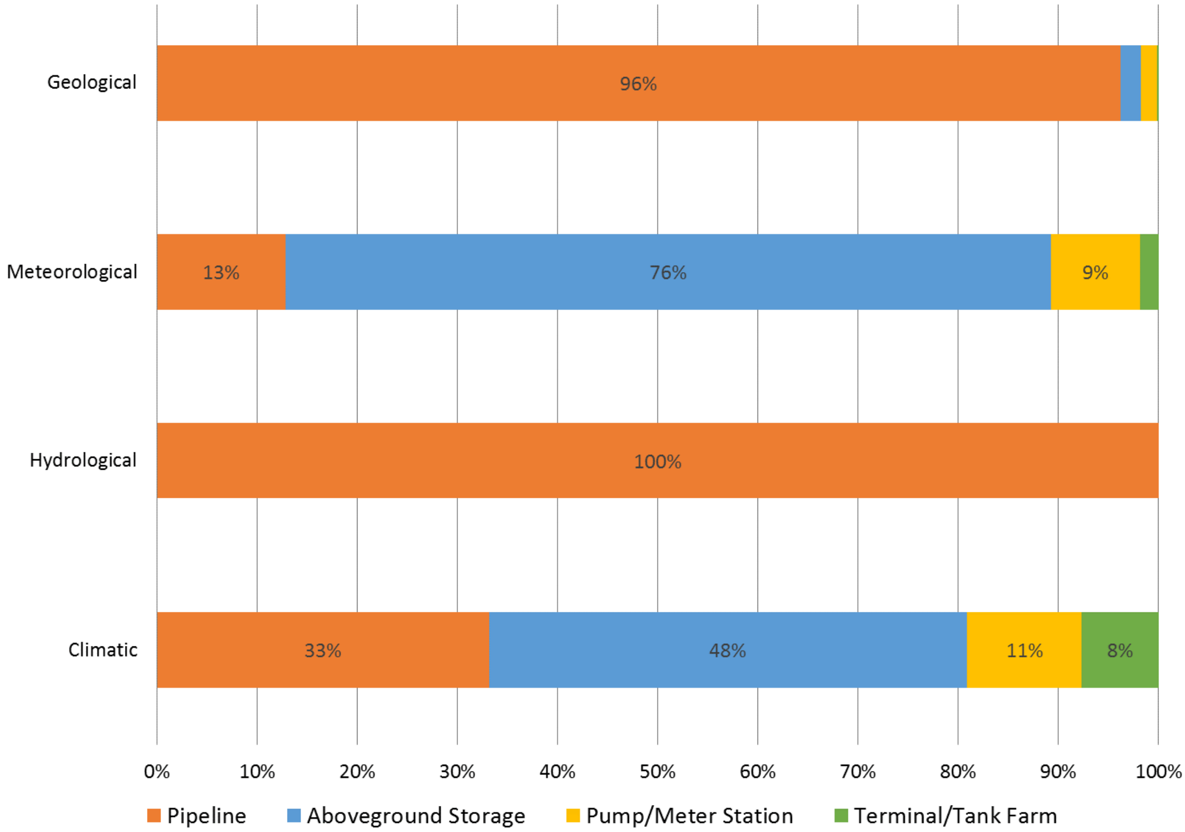


Figure 3.15. Distribution of systems parts with respect to hazard categories for release quantities

From the system part point of view, the majority of the natech releases occurred at pipelines with 218,400 BBL of total release which is about 70%. Aboveground storage units follow with 84,700 BBL. Releases from stations and terminals were found to be significantly lower with 12,800 BBL and 3,900 BBL, respectively. Pipelines were mostly and almost equally affected by geological and hydrological hazards based on release quantities (Figure 3.16). The contribution of meteorological and climatic hazards for this system part was less than 5% each. In contrast, more than 80% of the releases from aboveground storage units were due to meteorological hazards. Similarly, about 65% of the releases from stations were also related to meteorological hazards. In case of aboveground storage units, climatic hazards were in the order of 15% while geological hazards played a minor role. These hazard categories had slightly higher contributions for stations. Meteorological and climatic hazards dominated the natechs at terminals and each resulted in close to half of the releases in terms of quantity. There was a minor contribution from geological hazards. Hydrological hazards did not cause any substantial release at system parts other than pipelines, although they had a high percentage in terms of number of incidents at terminals.

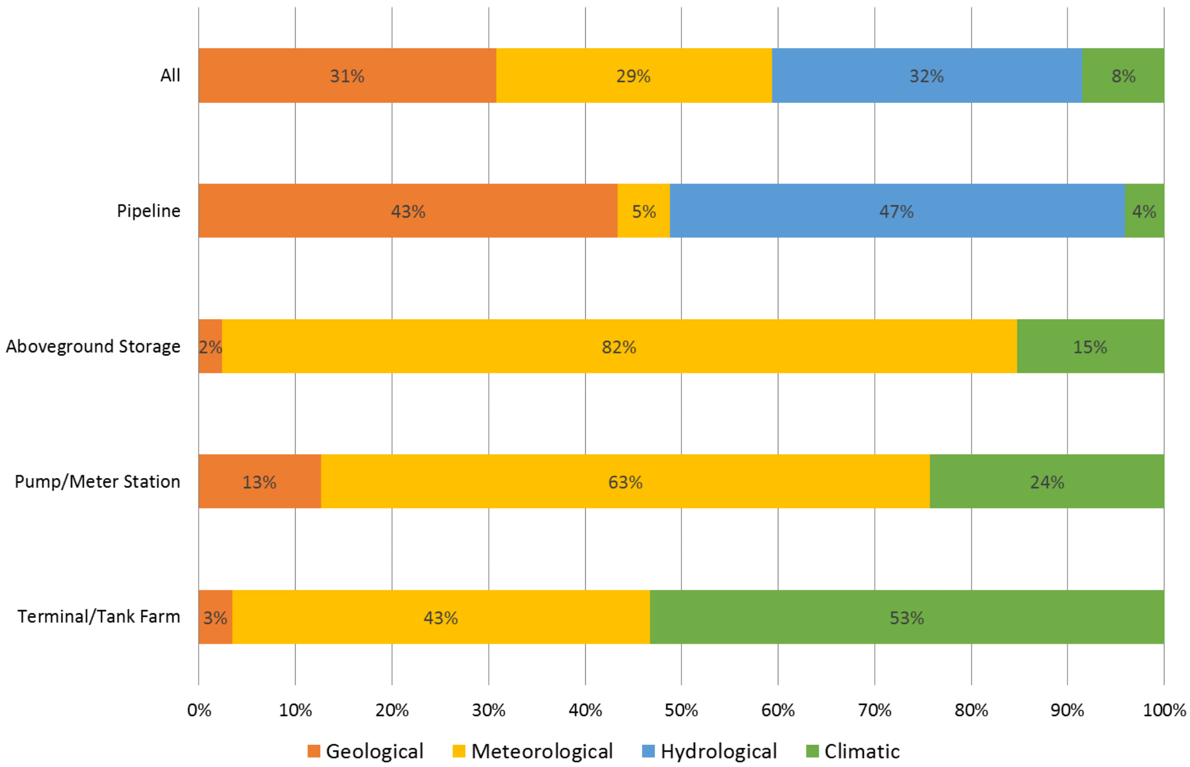


Figure 3.16. Distribution of hazard categories with respect to system parts for release quantities

Economic Cost

Similar to other reporting schemes, PHMSA incident reports provide not the actual, but the estimated cost of the incident losses. As indicated in Table 3.2, the reporting criterion related to the economic cost prior to 1994 considered only total property damage of the operator and other parties, whereas starting from 1994 additional cost items such as emergency response, environmental remediation, loss of product, and other costs were also considered. However, the reporting data format did not include separate fields for these cost items until 2002 and only the total costs were reported in 1994-2001. Therefore, the cost analysis was carried out separately for the periods 1986-1993 and 1994-2012.

In order to provide a common baseline, total economic losses were used for the analysis. Costs were adjusted for inflation effects by using annual gross domestic product (GDP) price indices published by the U.S. Bureau of Economic Analysis. For reasons of consistency with the summary statistics published by PHMSA, all values were adjusted for 2013 currency by using the index data for the fiscal year 2010 (BEA, 2010). Reported costs include only significant incidents and natechs. The yearly total cost of significant incidents and natechs is tabulated in Table 3.4 and the time series for the natechs is shown in Figure 3.17.

For the 1986-1993 period, the total economic cost of natechs, which only included property damage, was 8.4 million USD, whereas for all incidents it was 294 million USD. Therefore the natech contribution to the total property damage for this period is around 2.9%. The total cost of the natechs for the 1994-2012 period, which included costs of clean-up, recovery and lost product in addition to property damage, was 589 million USD. The total cost of all incidents during the period was slightly more than 3 billion USD. Based on these values, the natech contribution is 19.4% although in terms of the number of incidents this contribution is only 7.2%. Therefore, it can be concluded that natechs resulted in more severe economic damage per incident than other incidents if all costs are considered, although they occurred less frequently. A more detailed analysis of the natech contribution to the yearly occurrence and total cost distributions showed that the difference originates mainly from natechs that occurred in certain years, which are 1994, 1995, 2004, 2005, and 2011 (Figure 3.18). For all other years, the percentages of the number of natechs and total cost are not considerably different.

Table 3.4. Yearly total cost of significant incidents and natechs

	INCIDENT			NATECH		
Year	**# Incidents**	**Total cost (USD)**	**Total cost (USD 2013)**	**# Incidents**	**Total cost (USD)**	**Total cost (USD 2013)**
1986	193	14,868,000	27,499,000	8	580,000	1,072,000
1987	214	12,907,000	23,264,000	6	478,000	862,000
1988	165	31,683,000	55,366,000	6	136,000	237,000
1989	135	7,915,000	13,314,000	9	300,000	504,000
1990	137	14,946,000	24,241,000	4	269,000	435,000
1991	165	36,511,000	57,075,000	12	2,522,000	3,943,000
1992	165	35,036,000	53,425,000	5	58,000	88,000
1993	152	26,654,000	39,743,000	11	818,000	1,220,000
TOTAL	**1,326**	**180,520,000**	**293,927,000**	**61**	**5,161,000**	**8,361,000**
1994	176	60,790,000	88,734,000	21	35,600,000	51,965,000
1995	155	30,951,000	44,248,000	15	12,600,000	18,012,000
1996	171	83,939,000	117,738,000	7	428,000	601,000
1997	153	42,081,000	58,013,000	6	1,645,000	2,268,000
1998	131	52,123,000	70,996,000	11	4,754,000	6,475,000
1999	141	80,559,000	108,305,000	4	664,000	892,000
2000	128	131,497,000	173,287,000	6	2,132,000	2,810,000
2001	104	23,201,000	29,869,000	10	2,011,000	2,589,000
2002	129	46,514,000	58,758,000	7	322,000	406,000
2003	122	64,042,000	79,296,000	8	2,287,000	2,832,000
2004	125	83,643,000	100,938,000	13	19,992,000	24,125,000
2005	120	273,736,000	320,080,000	13	216,813,000	253,520,000
2006	104	56,427,000	63,817,000	5	7,027,000	7,948,000
2007	107	56,547,000	62,248,000	11	1,290,000	1,420,000
2008	119	132,846,000	142,840,000	6	12,135,000	13,047,000
2009	107	59,649,000	63,213,000	9	8,467,000	8,973,000
2010	119	996,456,000	1,045,486,000	12	36,266,000	38,051,000
2011	137	260,484,000	269,588,000	8	143,997,000	149,029,000
2012	125	138,757,000	141,255,000	6	3,748,000	3,815,000
TOTAL	**2,473**	**2,674,242,000**	**3,038,709,000**	**178**	**512,178,000**	**588,778,000**

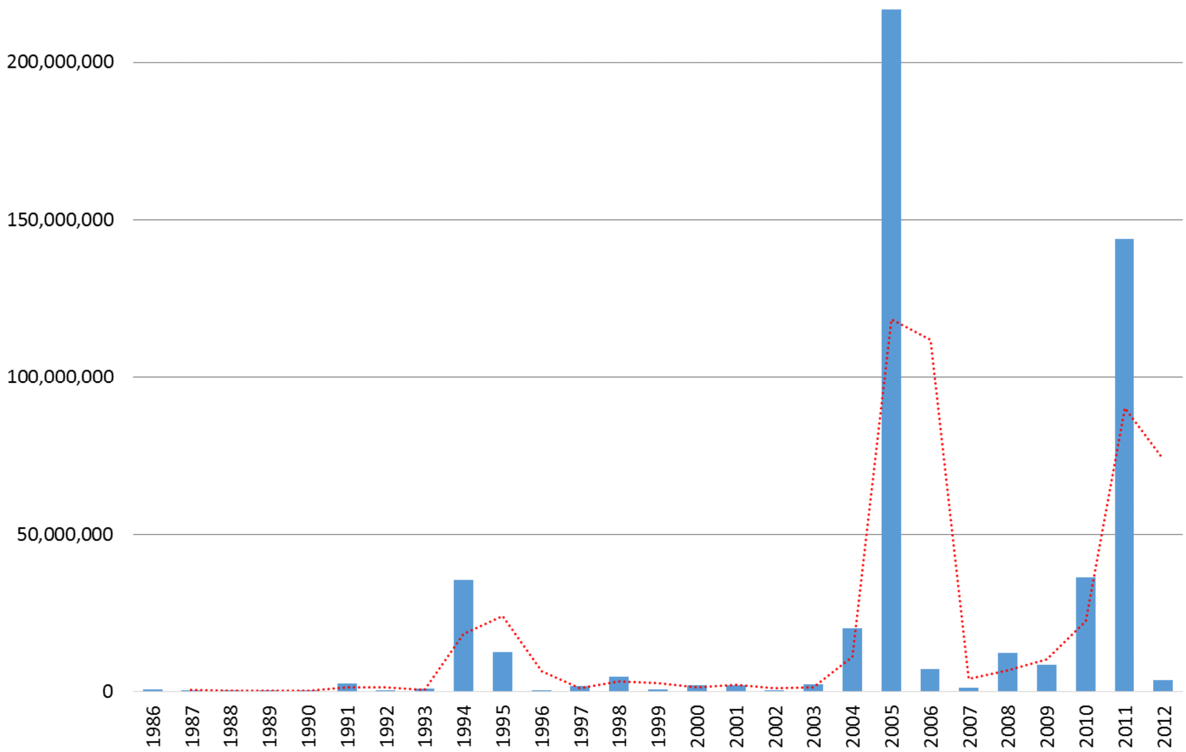


Figure 3.17. Yearly distribution of total economic cost of significant natechs

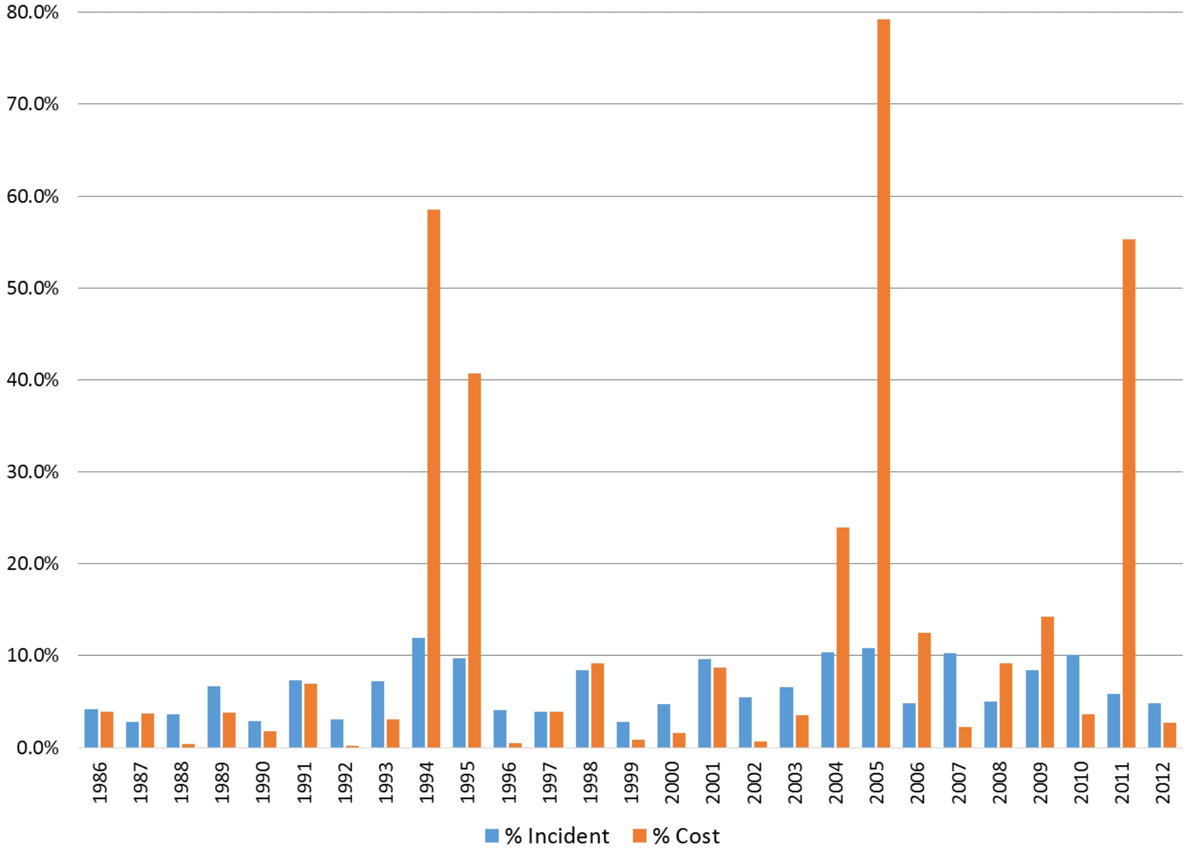


Figure 3.18. Percentage of natechs with respect to the number of incidents and total economic cost

Meteorological hazards, which resulted in 317 million USD total damage (54%), were found to be the main natural hazard category with respect to economic cost (Figure 3.19). Damage due to hydrological hazards corresponded to one third of the total cost (194 million USD), whereas geological hazards had only slightly more than 10% contribution (65 million USD). Within meteorological hazards, tropical cyclones made the most important contribution with 238 million USD (75%) followed by lightning events, which caused 68 million USD total damage (21%). Virtually all cost of hydrological hazards was due to floods (194 million USD), which was the second most costly natural hazard after tropical cyclones. Earthquakes had the highest share within geological hazards with 23 million USD (35%), followed by landslides (19 million USD, 30%) and subsidence (12 million USD, 18%). Among climatic hazards, cold weather related-natechs resulted in slightly more than 6 million USD (54%) damage.

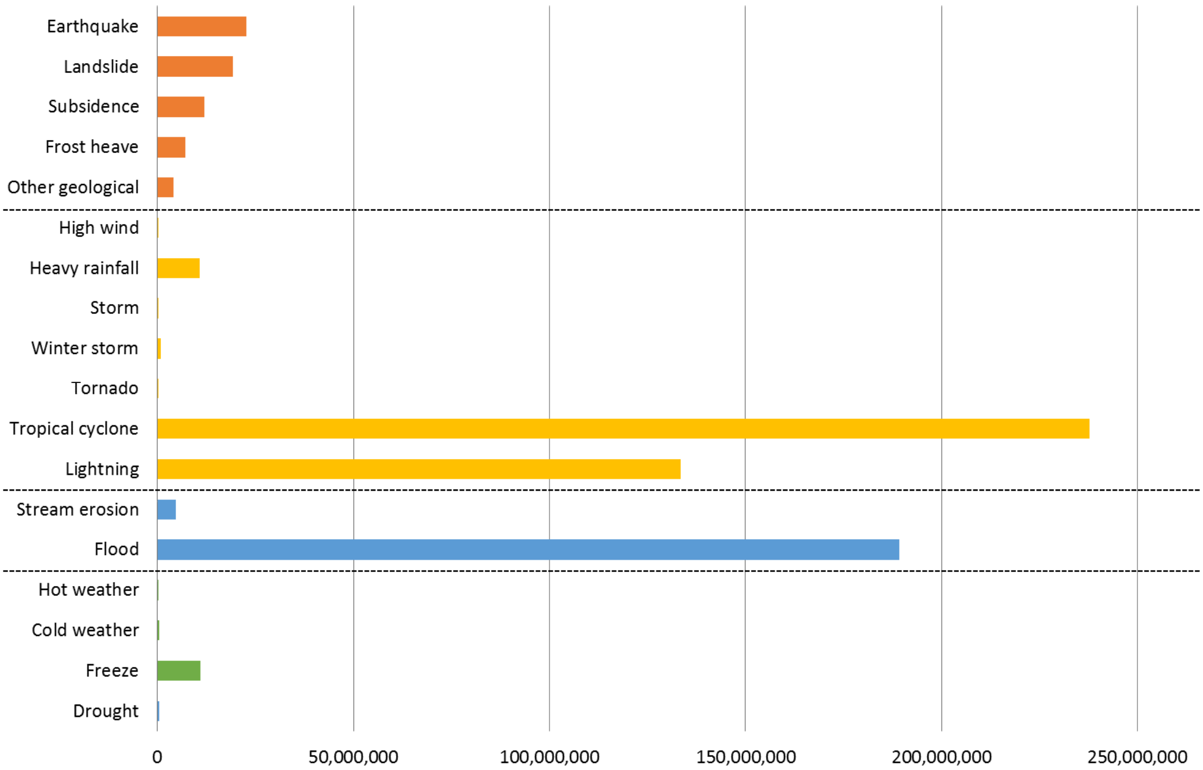


Figure 3.19. Distribution of total cost of natechs with respect to hazards

Almost all of the cost of pipeline natechs involving aboveground storage units was due to meteorological hazards (Figure 3.20). Meteorological hazards also resulted in the highest share of cost at terminals (78%, 6.4 million USD). The contribution of climatic and geological hazards to incidents at terminals was about 10% each. Among the natechs involving the pipe body, the majority of the cost was due to hydrological hazards (60%, 194 million USD), followed by geological (20%, 63 million USD) and meteorological (18%, 58 million USD) hazards. The effect of climatic hazards on pipelines in terms of economic cost was not significant compared to the other hazard categories. However, climatic hazards were the major hazard category for stations with more than 50% contribution (2.5 million USD). Meteorological hazards and geological hazards contributed 36% (1.7 million USD) and 9% (0.4 million USD), respectively.

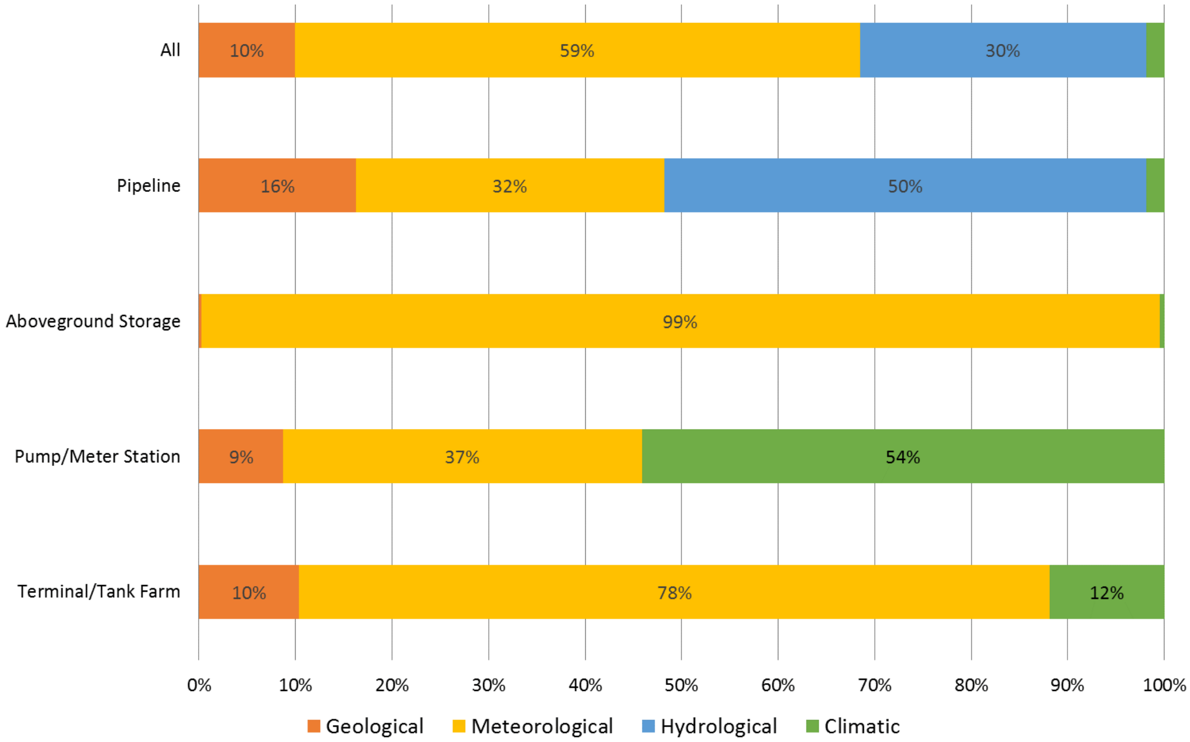


Figure 3.20. Distribution of hazard categories with respect to system parts for economic cost

From a system part point of view, almost all cost due to geographical and hydrological natechs are due to the incidents that occurred at the pipe body (Figure 3.21). Pipelines were also the major system part contributing to climatic natechs, followed by stations. However, the cost of pipeline incidents within meteorological hazards was only 18% (58 million USD) surpassed by aboveground storage units with a 79% contribution (251 million USD), the majority of which was due to tropical cyclones.

As shown in Figure 3.22, the histogram of yearly total cost for 1994-2012 indicates a skewed distribution with the majority of the yearly costs between 2.5-10 million USD. However, more than 50% of the total cost was due to two catastrophic events. The first one was due to the impact of Hurricane Katrina on a terminal facility located in Plaquemine, Louisiana on 29 August, 2005 (Incident #20050287). Due to the hurricane, the roof of one storage tank was ripped off and the foundation of another was ripped out (Sever, 2006). As a result, about 23,600 BBL crude oil was spilled, most of which was contained onsite where it naturally dispersed. The rest of the oil was contained by using mechanical booms and cleaned up with skimmers and in-situ burning. The reported estimated total cost of the incident was 175 million USD (28%). The second incident was a crude oil spill in the Yellowstone River in Laurel, Montana, which occurred on July 1, 2011 (Incident #20110262). The pipeline was exposed during flood and high water conditions that persisted for more than a month and failed at the girth weld as a result of external loading caused by exposure to flood conditions (Katchmar, 2012). About 1,500 BBL crude oil were spilled into the river resulting in a total estimated cost of 140 million USD (23%). These two natechs are among the top three most costly incidents of all the incidents within the study period. The only non-natech incident that resulted in a higher cost is the Kalamazoo River oil spill that occurred on 25 July, 2010 near Marshall, Michigan, which resulted in a spill of 20,000 BBL diluted bitumen with an estimated total cost of 813 million USD (Incident #20100181).

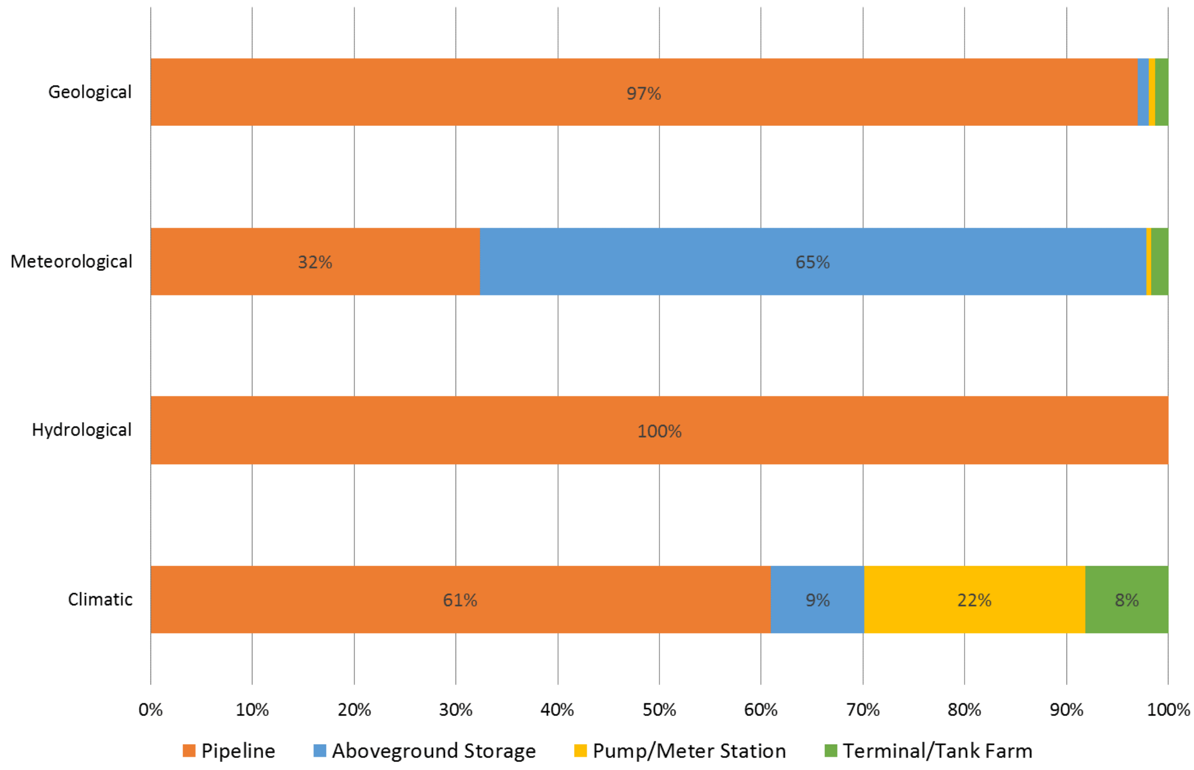


Figure 3.21. Distribution of system parts with respect to hazard categories for economic cost

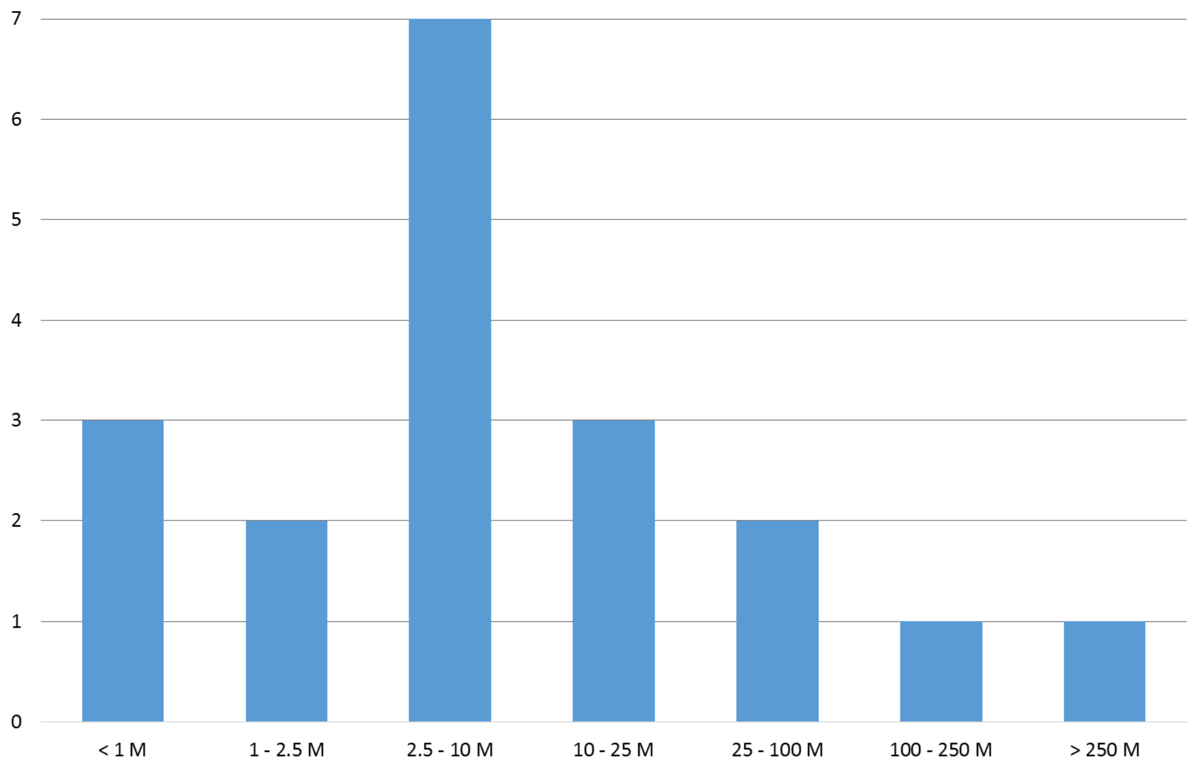


Figure 3.22. Histogram of yearly total economic cost of the significant natechs (1994-2012)

The most significant natech incidents with respect to total economic cost are listed in Table 3.5. None of the incidents in 1986-1994 have total costs high enough to be listed in the table, mainly because the costs included only the property damage. In fact, there is only one natech incident from this period with an adjusted reported cost greater than 1 million USD, which is the Brazos River flooding incident that occurred on July 7, 1991 near Knox City, Texas. Flooding water eroded the river bank, washed out the pipeline, and the stress of excessive water flow and debris caused an acetylene girth weld failure releasing about 6,250 BBL crude oil. The oil was widely distributed in flood-plain areas over 240 km (150 miles) along the river. The reported property costs were 2.2 million USD, however the total cost is likely to be higher due to extensive oil-restraining and clean-up activities that took place after the incident. Analysis of detailed cost data available for the 2002-2012 period shows that the operator and non-operator property damage costs correspond to only 20% (580 million USD) of the reported total cost of all incidents (2.9 billion USD). Emergency response (756 million USD, 26%) and especially remediation (slightly over 1 billion USD, 35%) costs are found to be more significant than the property costs. However, for natechs in the same period, the total property cost had the highest share in the total cost with 46% (230 million USD). Costs of product loss and remediation activities were found to be insignificant but emergency response costs were high (174 million USD, 35%). 175 million USD (76%) of the total property cost was due to a single natech incident, which is the terminal facility incident due to Hurricane Katrina in 2005 mentioned before (Incident #20050287). Apparently, for this incident all cost values except the property damage were reported as zero, which gives the impression that the total cost estimate couldn't be divided into categories and was reported as a single figure resulting in an imbalance in the cost data. Once this incident is excluded, the total contribution of property damage for all natech incidents reduces to 14%. Overall, it can be concluded that the property costs are only a fraction of the incident costs and hence the incidents in 1986-1993 should not be considered as less significant in the economic sense due to their low total cost values, which only include property damage.

It should be noted that costs were unavailable for several incidents and the reported values were also sometimes not accurate. For example, the cost of a pipeline rupture due to a landslide in Freeport, Pennsylvania, on March 30, 1990, which resulted in release of about 1,800 BBL of mixed petroleum products to the Ohio River (Incident #19900068) was reported as zero. Spilled products entered a small creek emptying into the Allegheny River and eventually the Ohio River, resulting in extensive ground and water pollution and interrupting the use of the Allegheny River as a water supply for several communities. According to the NTSB special investigation report, damage to the pipeline and environmental clean-up and restoration costs exceeded 19.5 million USD (12 million USD in 1990) (NTSB, 1996b). The actual cost of this incident alone is two times higher than the overall reported cost of all natechs in 1986-1993. Similarly, the release of more than 2,500 BBL of crude oil on October 8, 1994 into the Gum Hollow Creek that eventually entered Nueces and Corpus Christi Bays and impacted significant portions of existing freshwater and estuarine habitats, was reported to have zero cost. However, to settle two lawsuits related to the spill, the operator agreed to pay more than 66 million USD (45 million USD in 1994) (Associated Press, 2001). Solely with this figure, the incident should have been the third most costly natech incident in 1994-2012, however it was listed as one of the least costly ones. The uncertainty in the cost figures reported in the PHMSA dataset seems to be high, therefore they should be treated with caution.

Table 3.5. Most significant natech incidents with respect to economic costs in 1994-2012

Date	State	Substance	Hazard	System Part	NPS (")	Man. Year	Damage	Release Medium	Fire	Released (BBL)	Recovered (BBL)	Cost (M USD)	% Cost Yearly
2005-08-30	Louisiana	Crude Oil	Tropical cyclone	Aboveground Storage	-	-	Floor and roof damage	Soil	No	23,614	23,614	175.4	54.8
2011-07-01	Montana	Crude Oil	Flood	Pipeline	12	1990	Circumferential rupture	Stream	No	1,509	-	139.7	51.8
2010-06-12	Utah	Crude Oil	Lightning	Pipeline	10	1952	Pinhole leak	Stream	No	800	778	33.8	3.2
2005-09-02	Louisiana	Crude Oil	Tropical cyclone	Aboveground Storage	-	-	Floor damage	Stream	No	25,435	20,580	22.0	6.9
2005-09-02	Louisiana	Crude Oil	Tropical cyclone	Pipeline	20	1958	Rupture	Stream	No	3,245	-	17.8	5.6
2004-09-16	Louisiana	Crude Oil	Tropical cyclone	Aboveground Storage	-	-	Flood and roof damage	Gulf	No	3,148	-	17.7	17.5
1994-01-17	California	Crude Oil	Earthquake	Pipeline	10	1925	Rupture	Stream	No	4,207	1,360	17.5	19.7
2005-03-23	California	Crude Oil	Landslide	Pipeline	14	1950	Circumferential rupture	Lake	No	3,393	1,785	15.8	4.9
1994-10-20	Texas	Gasoline	Flood	Pipeline	40	1979	Rupture	Stream	Yes	20,000	-	14.6	16.5
1995-03-11	California	Crude Oil	Flood	Pipeline	18	1969	Circumferential rupture	Stream	No	4,000	-	14.3	32.3
2008-06-03	Kansas	Gasoline	Lightning	Aboveground Storage	-	-	Tank fire	No release	Yes	-	-	10.5	7.4
2005-01-26	Kentucky	Crude Oil	Subsidence	Pipeline	22	1950	Circumferential rupture	Stream	No	6,909	3,987	9.9	3.1
2011-08-13	Iowa	Gasoline	Flood	Pipeline	8	1993	Circumferential rupture	Stream	No	675	-	7.9	2.9
2006-06-12	Oklahoma	Gasoline	Lightning	Aboveground Storage	-	-	Tank fire	No release	Yes	-	-	6.7	10.4
1994-10-21	Texas	Crude Oil	Flood	Pipeline	20	1948	Rupture	Stream	Yes	5,350	2,900	6.5	7.4
2005-02-01	Pennsylvania	Gasoline	Cold weather	Pipeline	-	-	Valve failure	Soil	Yes	1,145	418	5.9	1.8
2009-12-23	Louisiana	Crude Oil	Flood	Pipeline	16	1965	Pinhole leak	Water	No	5	5	4.7	7.4
2005-08-29	Louisiana	Crude Oil	Tropical cyclone	Terminal	-	-	Piping failure	Stream	No	1,276	909	4.1	1.3
1994-01-21	Kansas	Diesel Fuel	Frost heave	Pipeline	8	1929	Rupture	Stream	No	3,869	3,535	3.4	3.9
1998-10-19	Texas	Crude Oil	Heavy rainfall	Aboveground Storage	-	-	Sunken roof	Stream	No	963	770	3.4	4.8
2004-09-16	Oklahoma	Crude Oil	Lightning	Aboveground Storage	-	-	Tank fire	No release	Yes	-	-	2.8	2.8
2009-04-24	Ohio	Propane	Lightning	Pipeline	12	1973	Puncture	Soil	No	173	-	2.5	4.0
1994-01-17	California	Crude Oil	Earthquake	Pipeline	10	1925	Circumferential rupture	Soil	No	561	100	2.3	2.6
1994-01-17	California	Crude Oil	Earthquake	Pipeline	10	1925	Circumferential rupture	Soil	Yes	561	100	2.3	2.6

Geographical Distribution

The regional distribution of significant natech incidents with respect to U.S. states is given in Figure 3.23 with the overlay of the current crude oil and hazardous liquid pipeline network and refineries of the U.S. The figure shows that the natechs are not uniformly distributed along the U.S., but concentrated in selected states. There were 34 states where significant natechs occurred during the study period (1986-2012).

Natural hazard type specific regional distribution of the natech incidents is summarized in Figure 3.24. Texas had the highest number of natechs corresponding to more than 27% of all natechs. 54% of the natechs in Texas were of meteorological origin and the remainder was almost equally distributed among the other hazard categories. Texas is followed by Oklahoma and Louisiana with more than 8%, and Kansas and California with more than 5% contributions each. Overall, slightly more than half of the natechs occurred in these 5 states.

Because the occurrence of incidents is also influenced by the pipeline network density, it is not possible to attribute the high or low number of natech incidents solely to the natural hazard susceptibility of these states. In fact, a comparison of incident and natech occurrence ratios of the states shows that there is no significant difference between the occurrence of incidents and natechs (Figure 3.25).

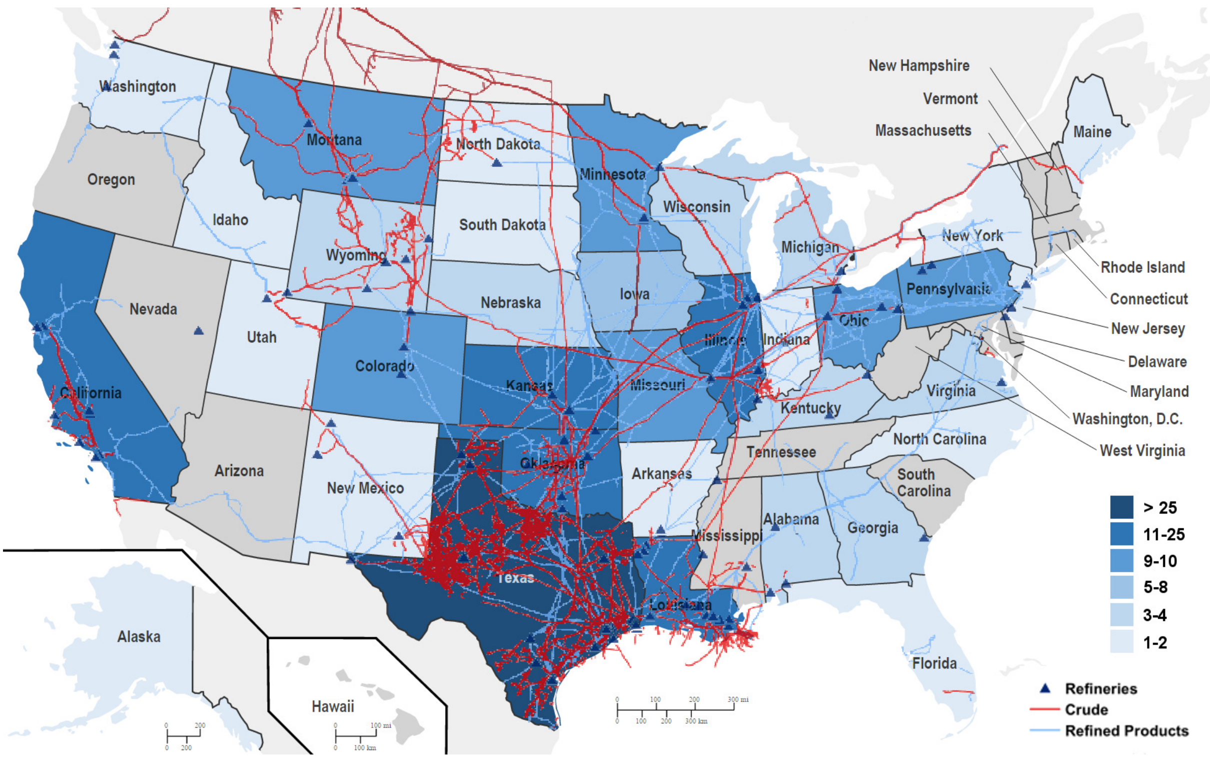


Figure 3.23. Geographical distribution of significant natech incidents by U.S. states

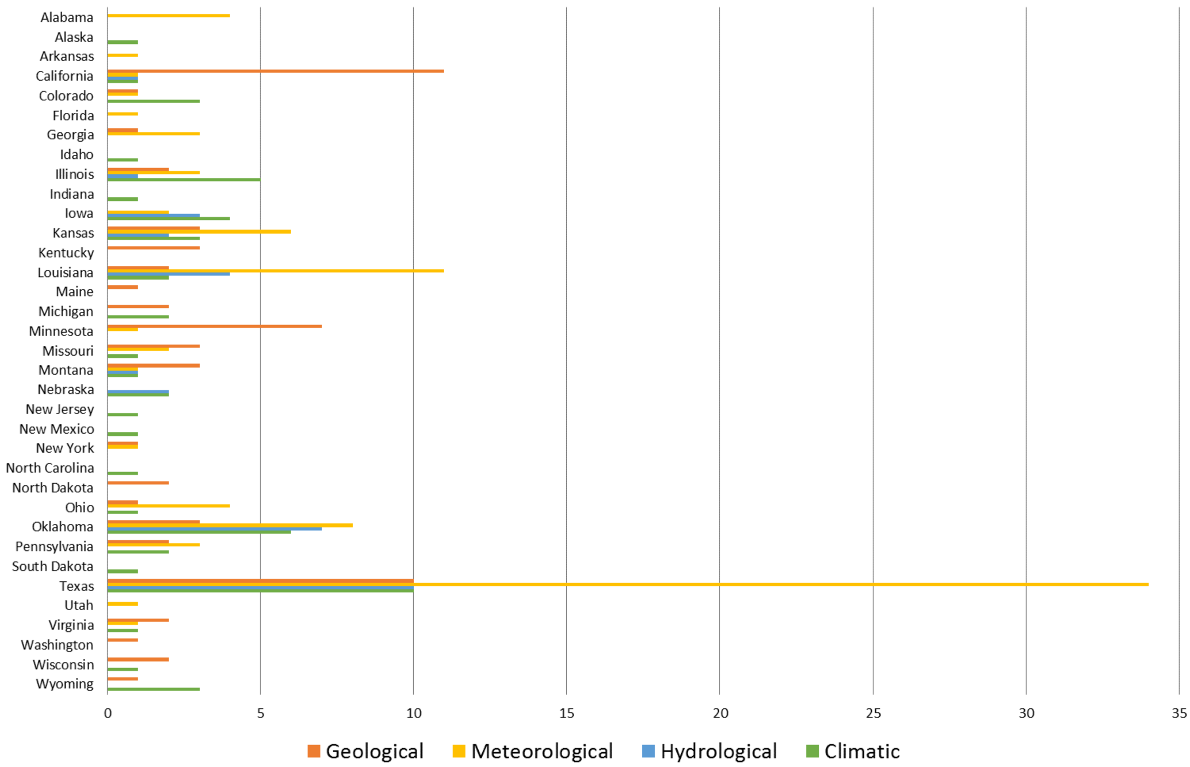


Figure 3.24. Distribution of hazard categories with respect to regions

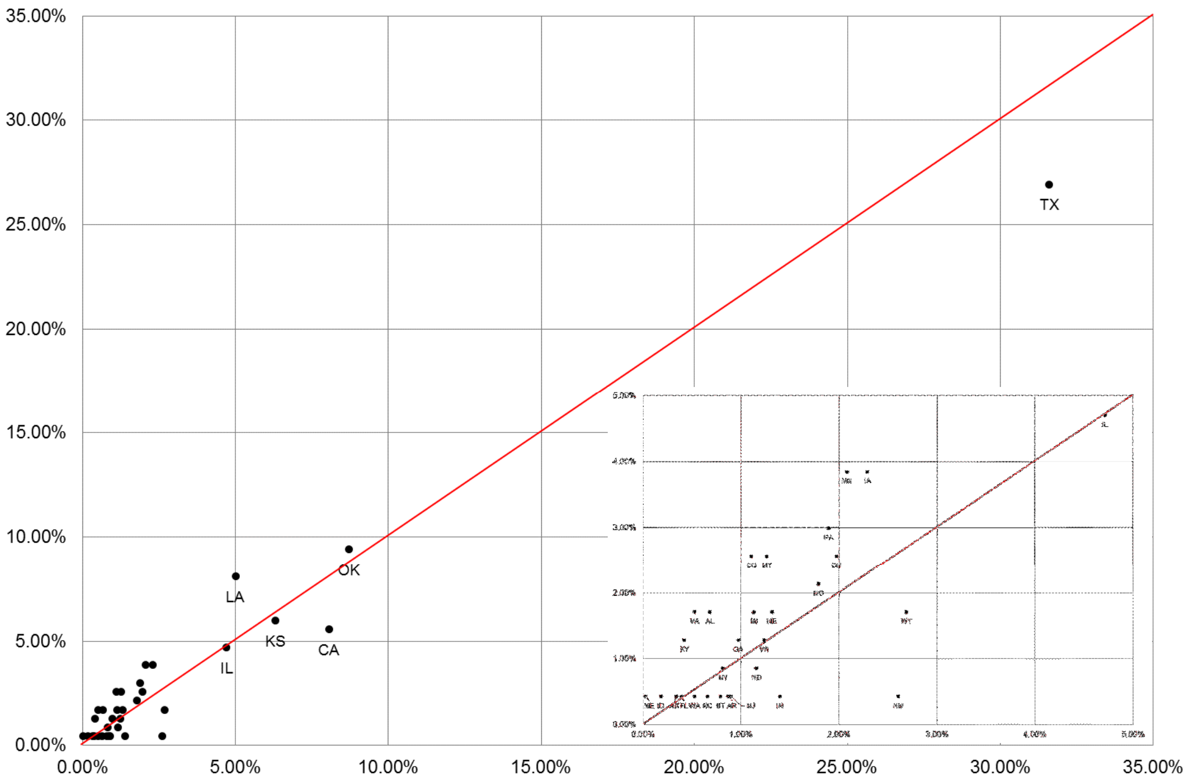
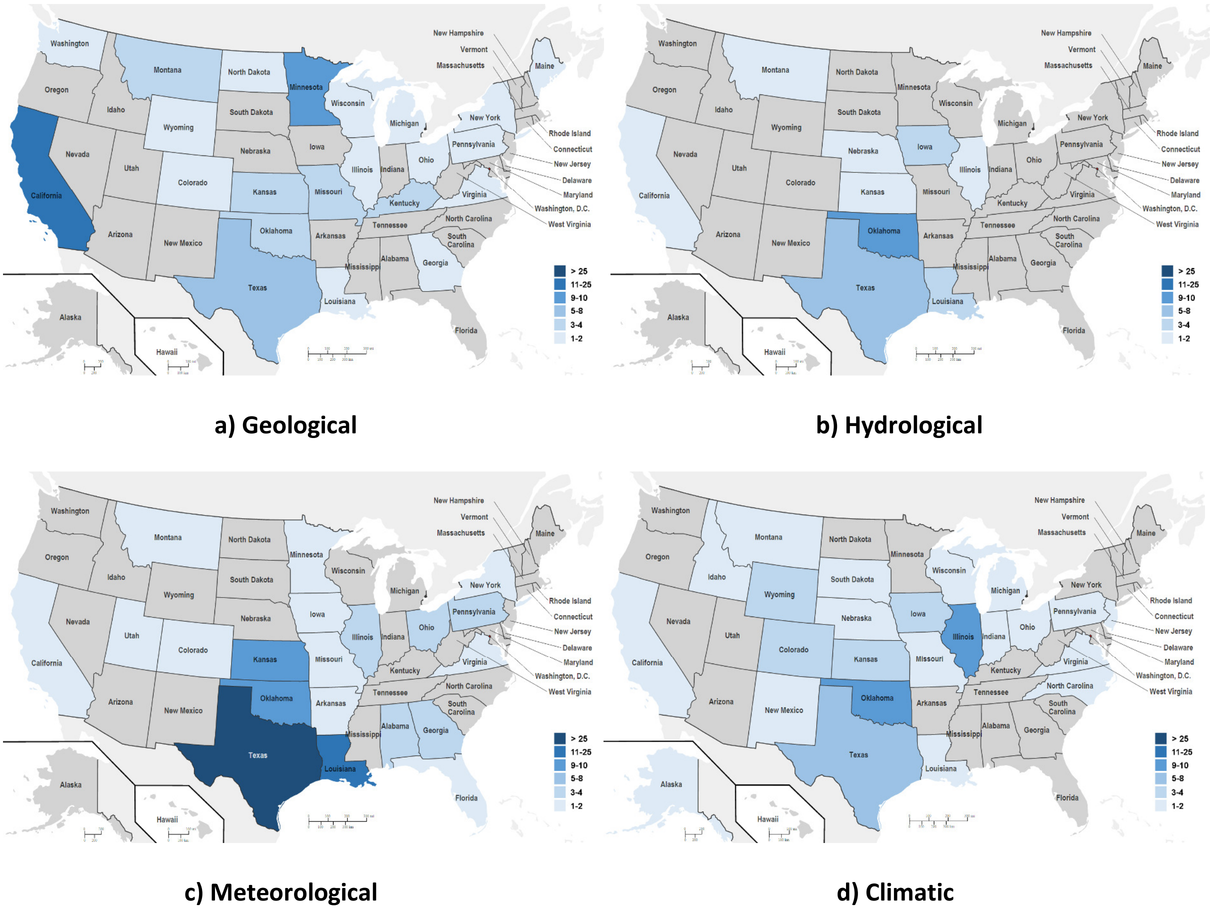


Figure 3.25. Comparison of regional incident and natech occurrence ratios

States with the highest number of natechs also had the highest number of incidents. Among the states having experienced 4 or more natechs, geological hazards were the dominant trigger in California (85%), Minnesota (77%), Michigan (50%), Missouri (50%), Montana (50%), and Virginia (50%). Incidents caused by meteorological hazards were observed more frequently in Alabama (100%), Ohio (67%), Louisiana (58%), Texas (54%), Pennsylvania (43%) and Kansas (43%). In terms of number of incidents, hydrological hazards played a minor role, except in Nebraska where they were equal in number with climatic hazards. Climatic hazards dominated only in Wyoming. The overall regional distribution of the number of natechs with respect to natural hazard categories is summarized in Figure 3.26.



a) Geological

b) Hydrological

c) Meteorological

d) Climatic

Figure 3.26. Geographical distribution of significant natech incidents by U.S. states and hazard type

For almost all states, pipeline natech incidents are not uniformly distributed geographically, but concentrated in specific counties. Figure 3.27 reveals that some of these counties are located at intersection points of multiple pipeline segments where pipeline densities are high. However there are also counties, which are located at similar settings, but didn't have any pipeline natechs in the past.

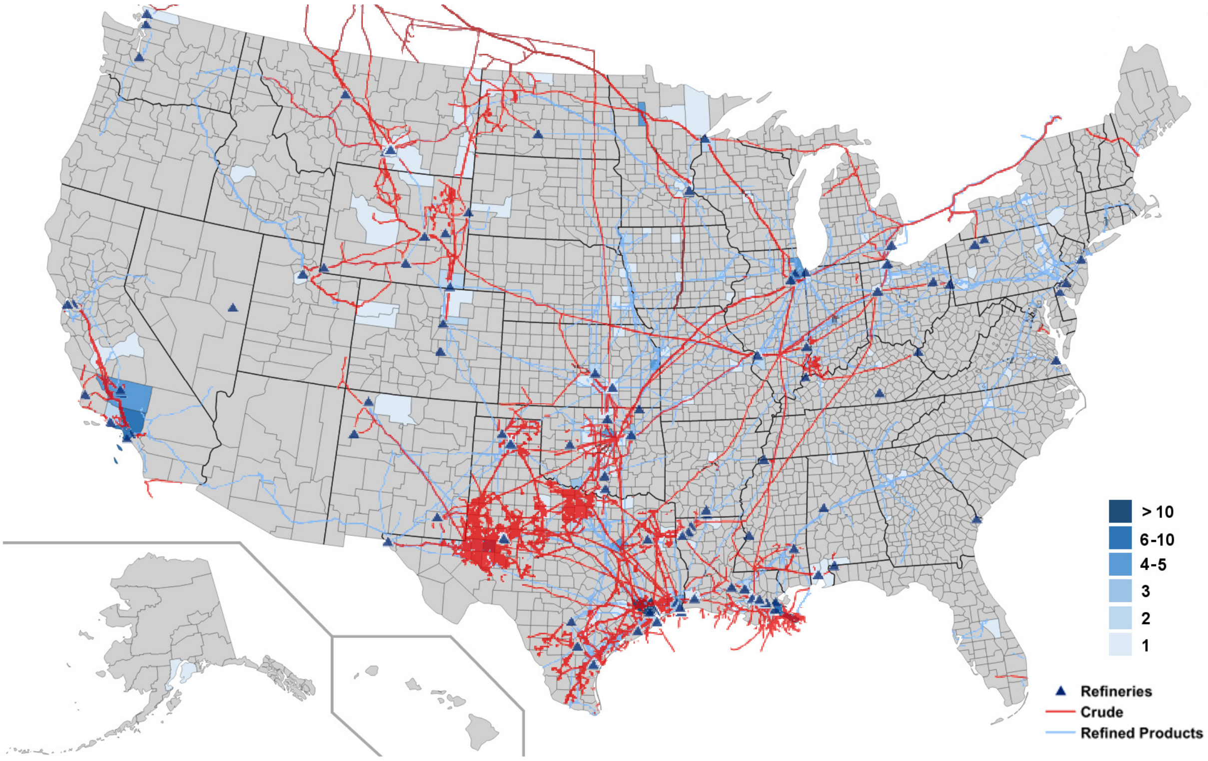


Figure 3.27. Geographical distribution of significant natech incidents by county

The majority of the states experienced less than 10,000 BBL total substance release. There were 4 states with more than 20,000 BBL of release, which were Texas (91,700 BBL), Louisiana (62,900 BBL), Oklahoma (43,600 BBL), and North Dakota (27,700 BBL). In Oklahoma and Texas, although less important in terms of trigger frequency, floods caused the biggest amount of released substance. For Louisiana, the triggers causing the biggest releases were almost completely meteorological involving tropical cyclones, whereas geological hazards were the main hazards in North Dakota. Among the states having 4 or more natechs, geological hazards resulted in major proportions of releases in California, Colorado, Georgia, Kansas, Michigan, Minnesota, Montana, Pennsylvania, Virginia, and Wyoming. In addition to Louisiana, meteorological hazards were also the major release trigger in Alabama. In Illinois and Iowa, hydrological hazards resulted in more release, whereas in Missouri and Nebraska the major natural hazard contribution was from climatic hazards.

While Texas has the highest number of incidents, in terms of economic losses in 1994-2012 it is outranked considerably by Louisiana (248 million USD, 97% meteorological), Montana (141 million USD, 99% hydrological), and California (55 million USD, 73% geological and 27% hydrological). The economic damage experienced in Texas was only 38 million USD, which was mainly due to hydrological and meteorological hazards. It is followed by Utah which had 34 million USD damage, all due to meteorological hazards. These 5 states together constitute about 88% of the total natech cost. Among the other states having more than 5 million USD economic cost, meteorological hazards were the major contributor in Kansas (10.5 million USD, 73%) and Oklahoma (10 million USD, 82%). In Kentucky, all natech damage was due to geological hazards (10 million USD). Hydrological hazards were the primary source of losses in Iowa (7.9 million USD, 87%), whereas in Pennsylvania it was climatic hazards (7.2 million USD, 95%).

Substance Type

In order to analyse the distribution of incidents with respect to the type of hazardous substance transported through the pipeline systems, the substances were divided into 4 categories: crude oil, non-HVL refined and/or petroleum products which are liquid at ambient conditions, HVL or other flammable or toxic fluids which are gaseous at ambient conditions, and CO_2. 46% of the incidents are crude oil incidents, followed by non-HVL and HVL incidents with 35% and 18% contribution, respectively. CO_2 incidents were only 1% of the natech incidents (Figure 3.28).

Because the lengths of the pipeline systems for different substances are not equal, a direct comparison of the number of incidents is not appropriate. A low number of incidents does not mean that the related system is less vulnerable to natural hazards. Mileages for different categories of the hazardous liquid pipelines in the U.S. are available only starting from 2004, therefore a historical comparison of incident rates with respect to pipeline system lengths is not possible for the majority of the data. However, taking the last mileages given in Table 3.1 into consideration, the number of natech incidents per existing 1,000 km unit length of pipeline are found to be 1.2, 0.8, 0.5, and 0.4 for crude oil, non-HVL, HVL, and CO_2 pipelines, respectively. The overall value for all natechs is 0.8 for approximately 300,000 km total length of hazardous liquid transmission pipelines.

45% of the HVL natechs involve gasoline, whereas 39% involve other liquid fuels such as diesel, fuel oil, kerosene, and jet fuel. Mixtures of refined products (e.g. transmix) correspond to 8% of the natechs and the remaining 7% includes other non-HVL products. Among HVLs, liquefied petroleum gases (LPG) and natural gas liquids (NGL) are the most frequently observed substances with 84% contribution. 9% of the HVL natechs involve anhydrous ammonia and the remaining 7% are other HVLs (Figure 3.28).

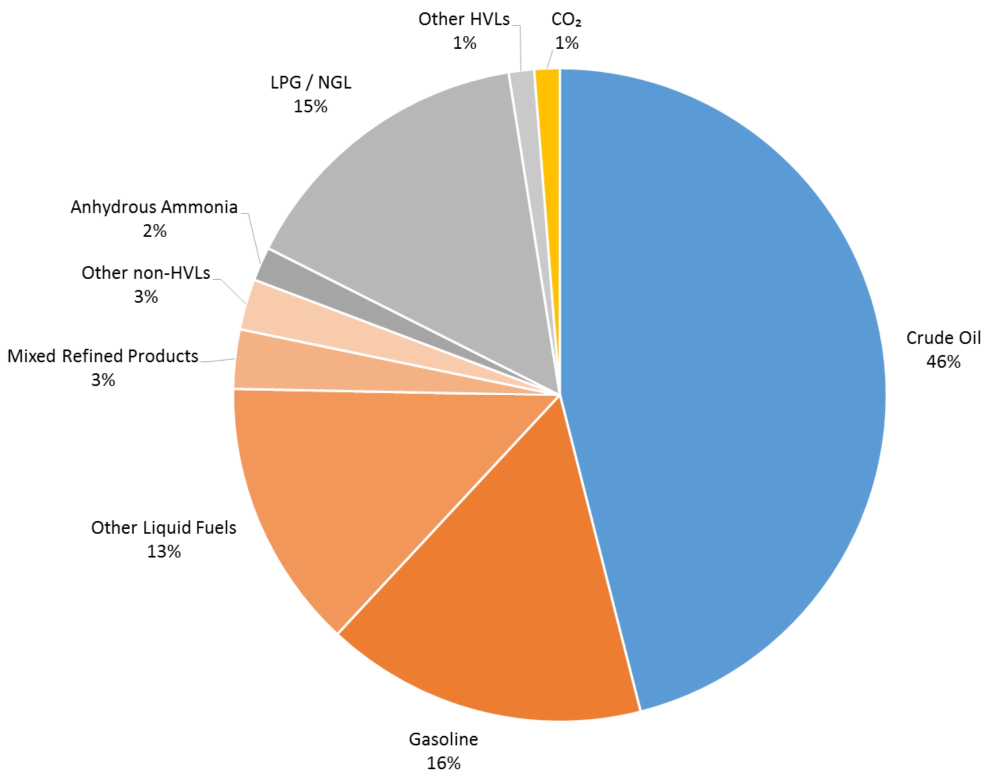


Figure 3.28. Distribution of natech incidents with respect to substance

A comparison of significant and non-significant natechs in the period 2002-2012 shows that the percentages of significant and non-significant natechs are almost the same for crude oil and non-HVL incidents. However, HVL natechs tend to be more significant (75%) rather than non-significant (25%) (Figure 3.29).

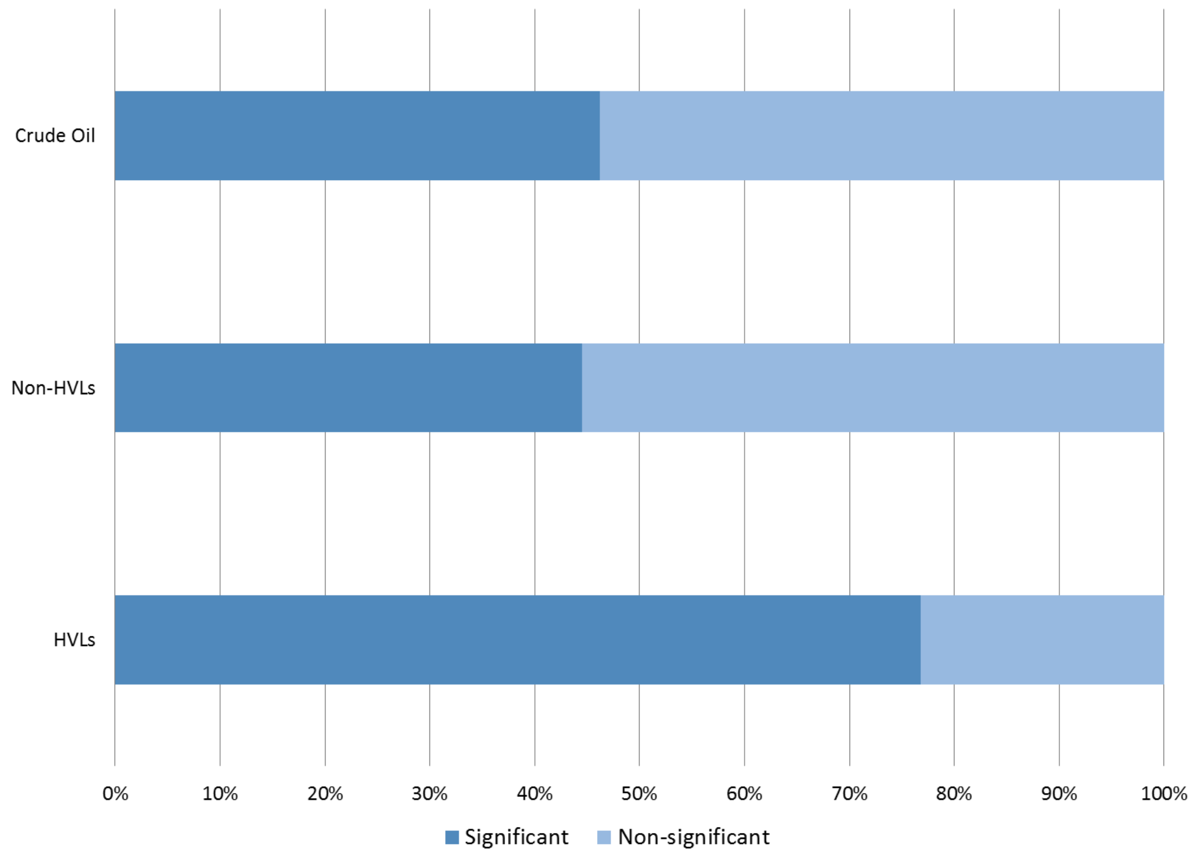


Figure 3.29. Comparison of significant and non-significant natechs with respect to substance type

Pipe Characteristics

The majority of pipelines affected by natural hazards were between 6"-12" in nominal pipe size. The highest number of natechs occurred at 8" and 10" pipelines (Figure 3.30). Beyond 12" there were only one or two incidents for most of the pipe sizes, the highest number being 5 and 4 for 24" and 26" pipelines, respectively.

There is no directly observable difference between the pipe size distributions of different hazard categories, except for climatic hazard triggered incidents which were not observed in above 10" diameter pipelines (Figure 3.31). The situation was also similar with respect to substance type. Although there were more incidents at selected pipe sizes, natechs involving crude oil and non-HVL substances were observed for the whole range of pipe sizes. For HVL pipelines, there was only one incident above 12" which involved a 30" pipeline (Figure 3.32).

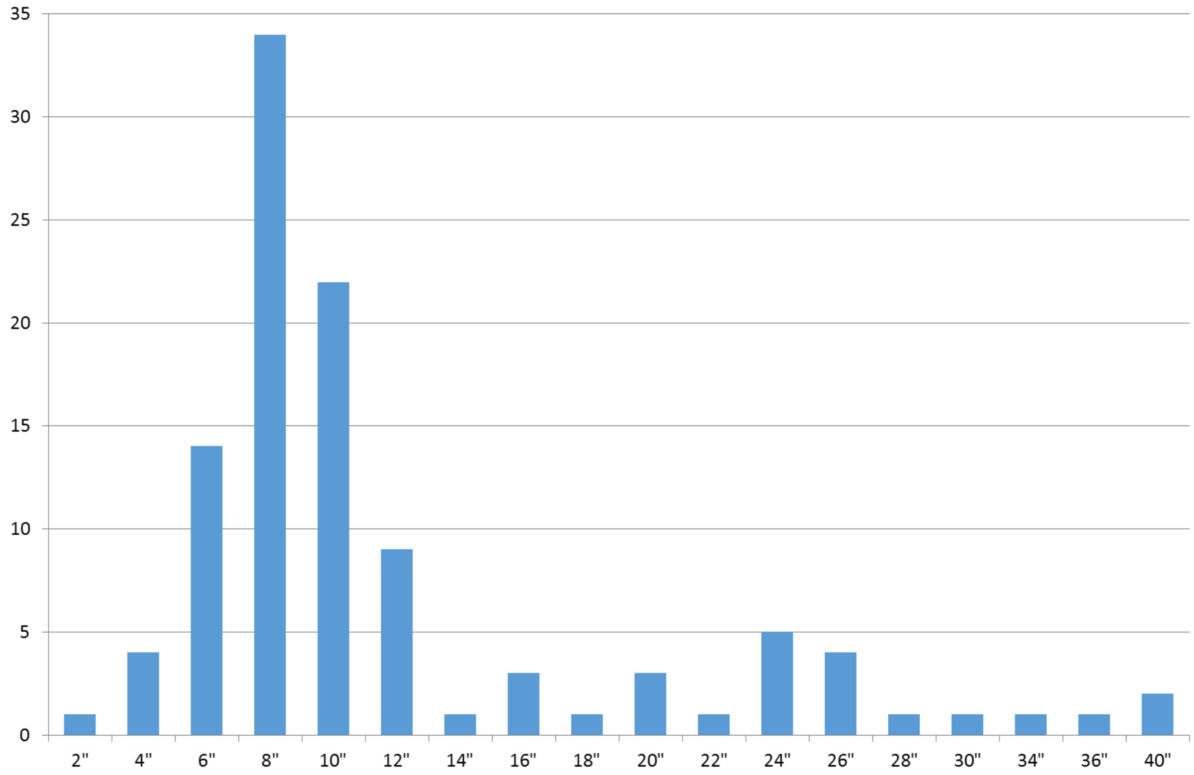


Figure 3.30. Diameter distribution of natechs involving the pipe body

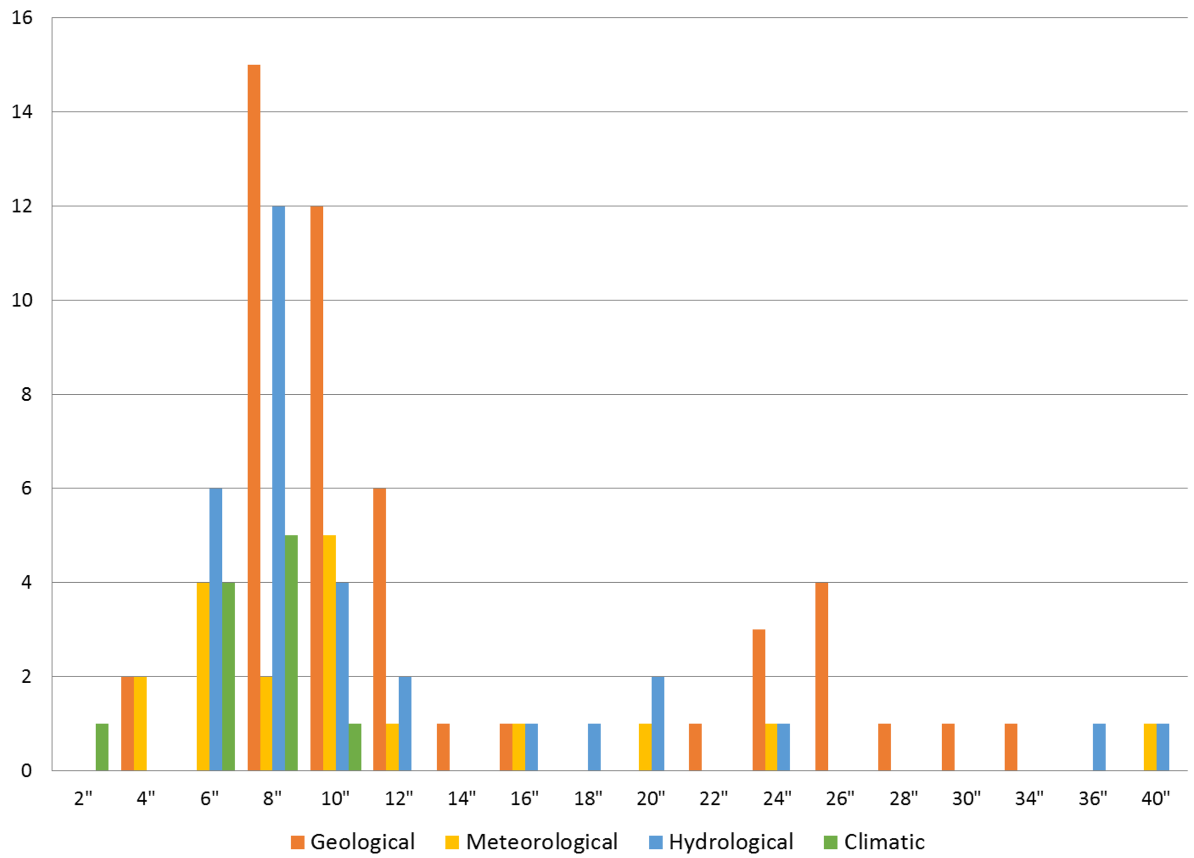


Figure 3.31. Diameter distribution of natechs involving the pipe body with respect to hazard category

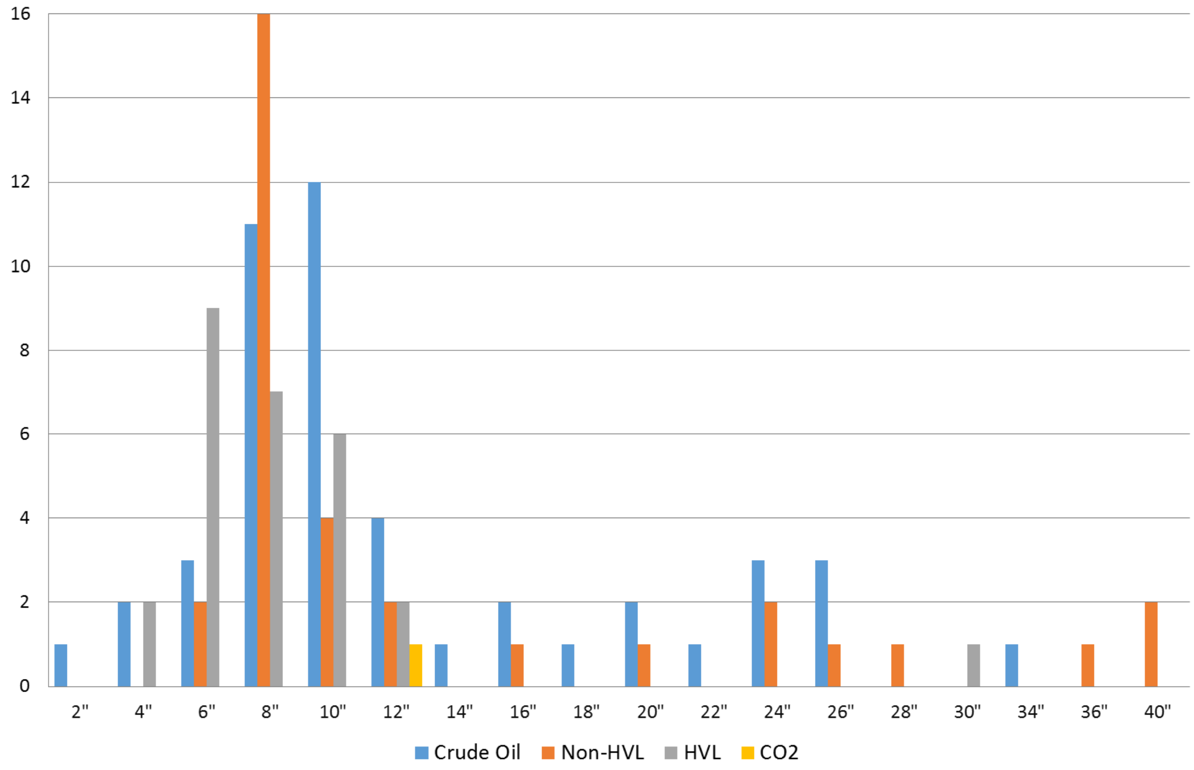


Figure 3.32. Diameter distribution of natechs involving the pipe body with respect to substance type

The histogram of the pipe age for the natechs involving pipelines shows a slightly right skewed normal distribution towards pipelines aged 20-29 years with a distribution mean of 40-49 years (Figure 3.33). The number of incidents involving very old (≥ 70 years) and relatively new (< 20 years) pipelines is low. The majority of the pipes are found to be in the age range of 20-49 years.

Overall, incidents related to all natural hazard categories are found to be evenly distributed within the 0-80 year age range. The only exception are meteorological hazards, which were not observed in pipelines older than 60 years (Figure 3.34).

With respect to substance type, incidents involving crude oil are found to have occurred comparatively more frequently in older pipes, whereas non-HVL and HVL incidents involve medium aged and relatively new pipelines, respectively. This can be seen in the 2-year moving average trend lines of the natechs with respect to age and substance type (Figure 3.35).

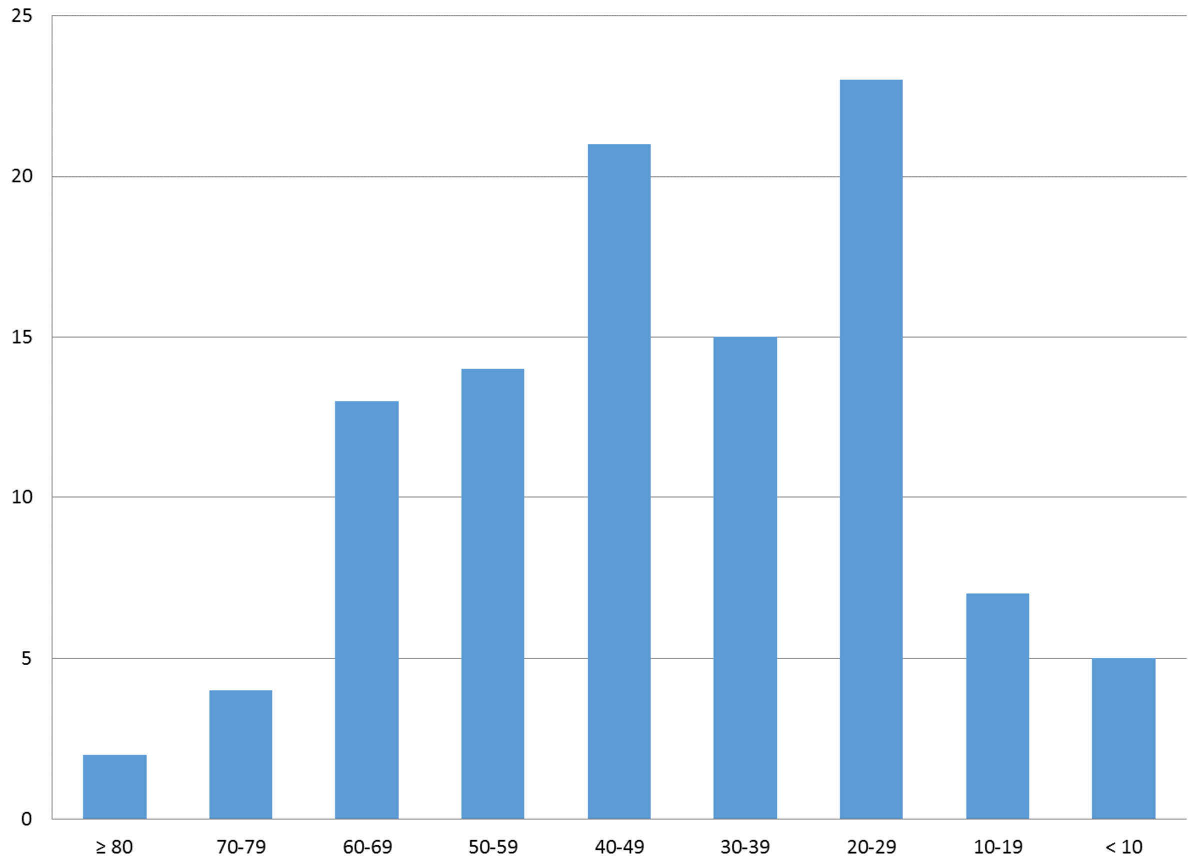


Figure 3.33. Age distribution of natechs involving the pipe body

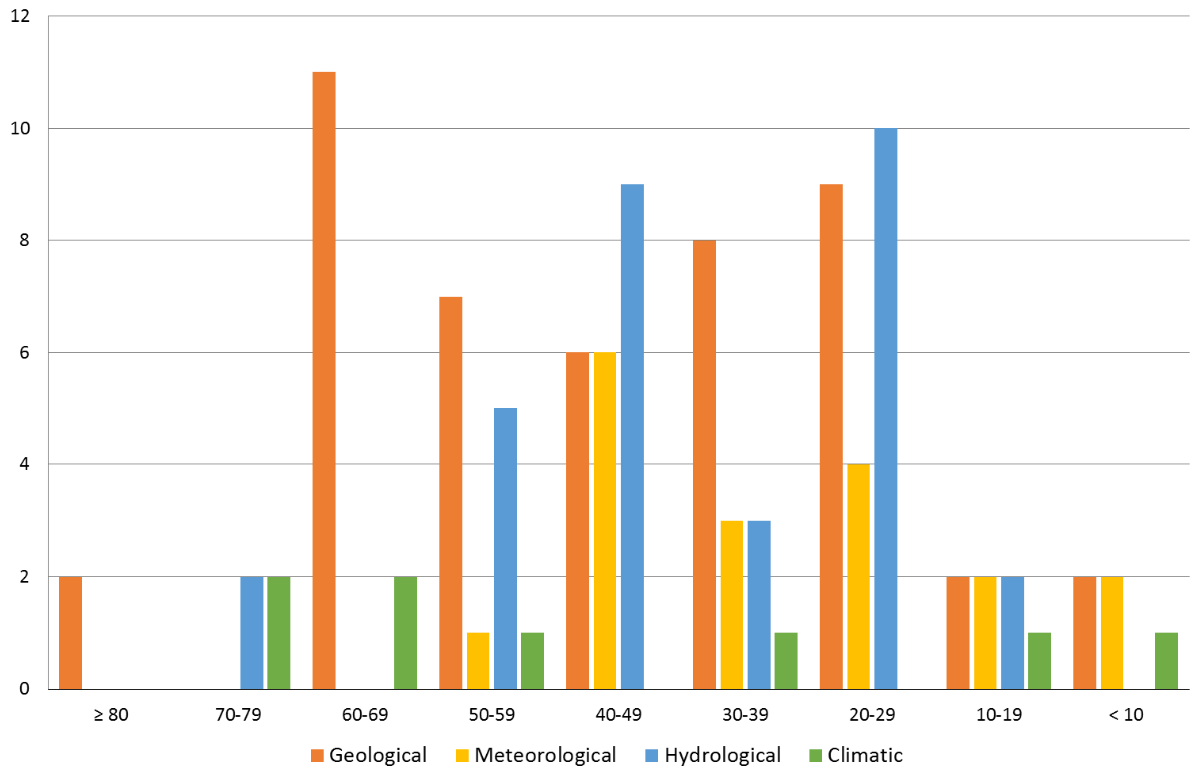


Figure 3.34. Age distribution of natechs involving the pipe body with respect to hazard category

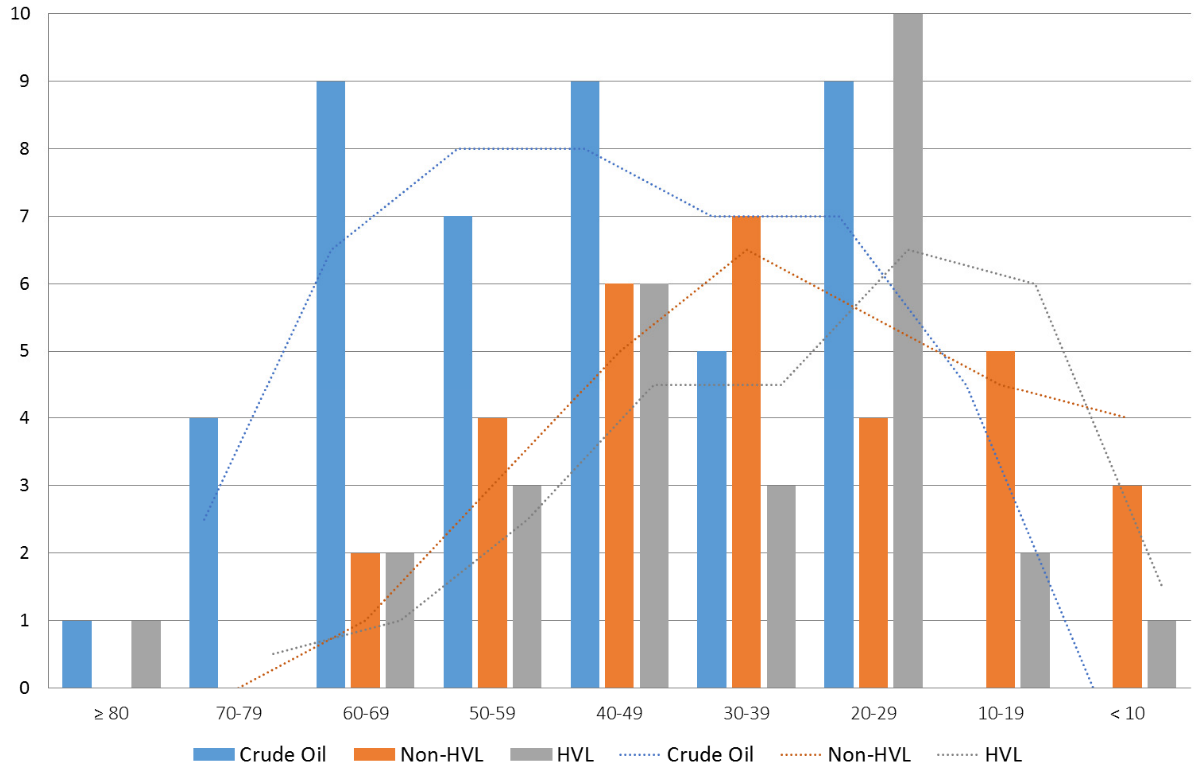


Figure 3.35. Age distribution of natechs involving pipe body with respect to substance type

Release Medium

Information on the medium into which the hazardous liquids are released is available in the reporting formats used during 2002-2012, but it is missing in the reporting format and corresponding PHMSA dataset for 1986-2002. Based on the incident narratives and supplementary information available in the NRC reports and other references, release medium information was completed for all natech incidents. According to the collected data, 16% of the natechs resulted in releases to the atmosphere. In 10% of the incidents, the released substance was directly consumed by fire resulting in zero net release to the environment. Releases to water bodies, including inland and sea waters, correspond to 28%, whereas releases to the soil including dikes and secondary containments were 46% (Figure 3.36). Hydrological hazards resulted in releases only to the water environment, which was in most cases freshwater streams (88%). For climatic incidents the major release medium was soil (82%). Although for geological and meteorological incidents the main release medium was also soil (56% and 36%), atmospheric releases and spills to water bodies were also common. All releases with zero net accumulation of the released substance due to fire consumption were meteorological, more specifically lightning incidents, except one case which was related to heavy rain (Figure 3.37). With respect to substance type, crude oil and non-HVL substances show a similar pattern in which the majority of the releases (55-60%) were to the soil, followed by about 30% of releases to the water, and the remainder (10-15%) as zero net release. All HVL and CO2 releases were to the atmosphere, except the releases that occurred at river crossings which were directly to the water (21%). With respect to the system part, incidents involving pipelines resulted in the highest number of releases to water bodies (86%). For all other system parts, releases to the water were minor and the main release medium was soil. For aboveground storage tanks atmospheric releases were very rare and the second major release type was zero net release with 31% contribution.

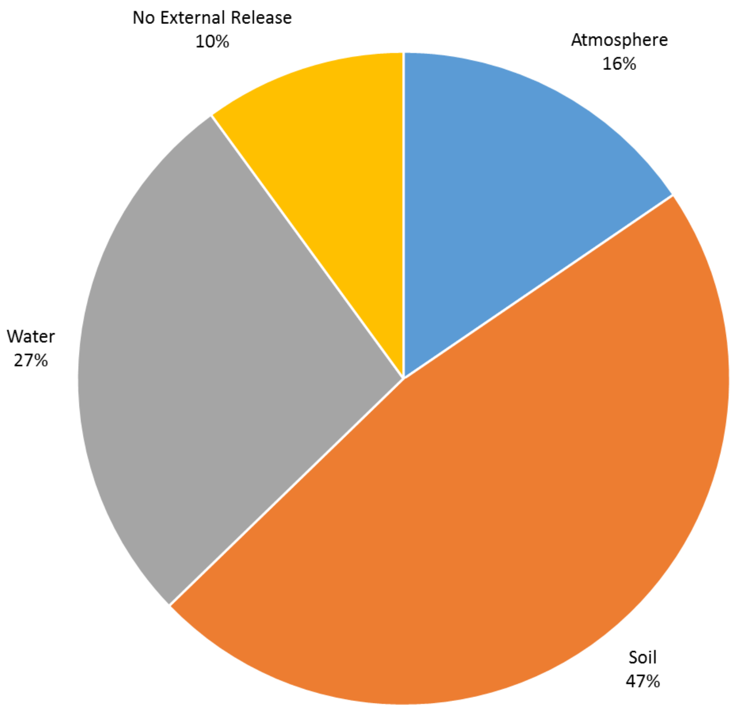


Figure 3.36. Distribution of natechs with respect to release medium

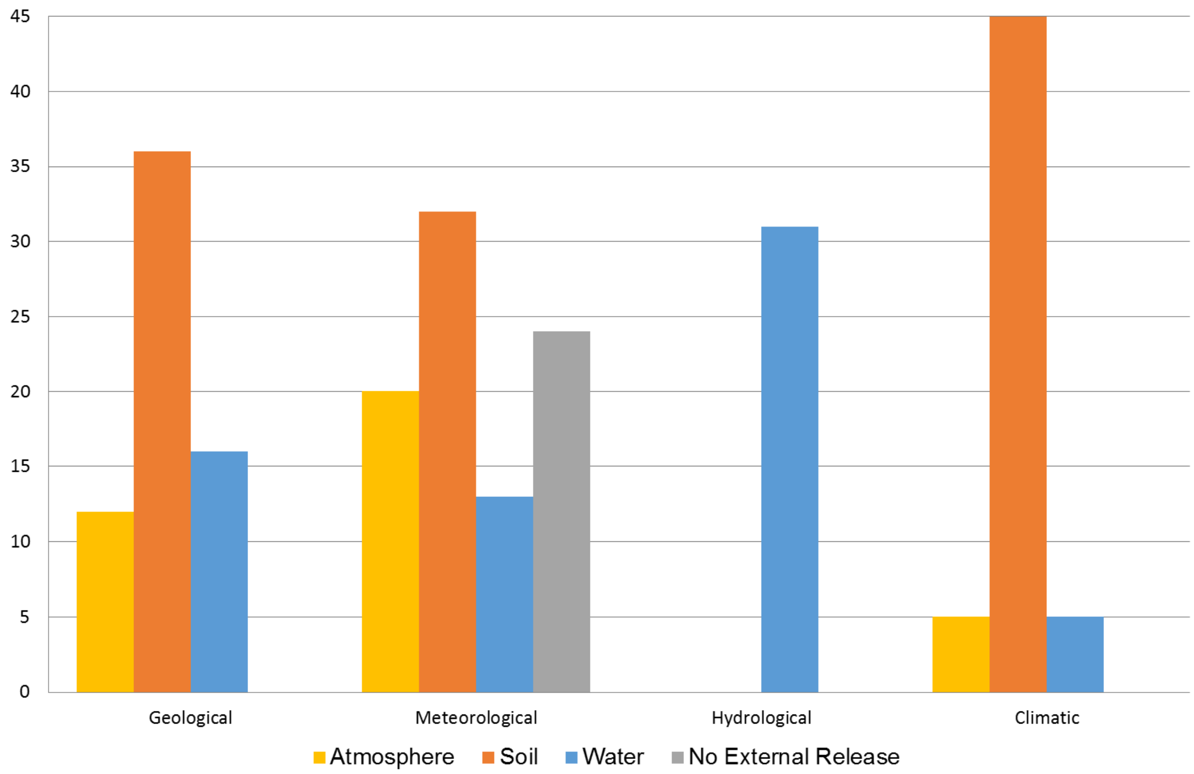


Figure 3.37. Distribution of natechs with respect to release medium and hazard category

Damage and Impact Modes

About 55% of the natech incidents involving the pipe body resulted in rupture, whereas the remaining 35% and 10% were leaks and component failures (at valve sites), respectively. Ruptures were dominant for hydrological (90%) and geological (60%) hazards, while leaks were more frequently observed for meteorological (70%) and climatic (45%) hazards (Figure 3.38).

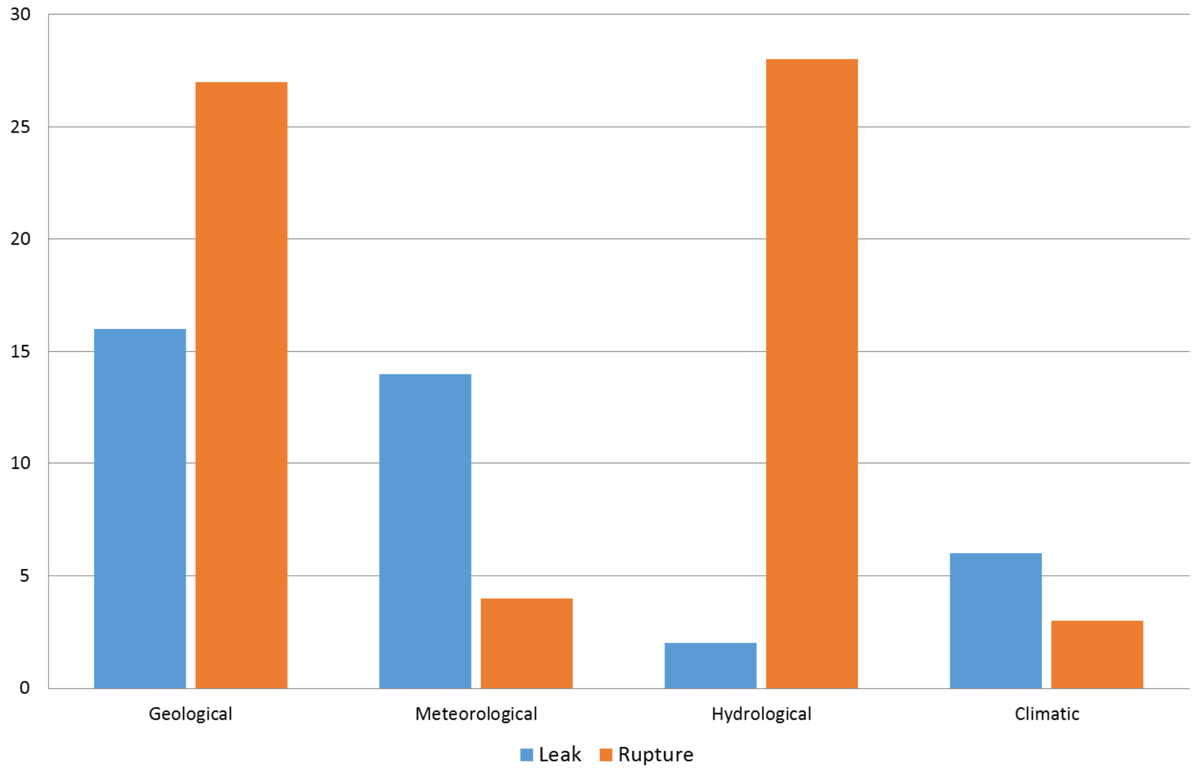


Figure 3.38. Distribution of pipe damage modes with respect to hazard category

All earthquake and landslide natechs, and the vast majority of flood and subsidence natechs resulted in ruptures. In contrast, all resting rock and the majority of the lightning natechs involved leaks. For selected hazards, such as storm, tropical cyclone, frost, and drought, the number of incidents was not high enough to draw a statistically meaningful conclusion (Figure 3.39).

The impact modes of natural hazards on different parts of the pipeline systems are diverse and highly specific to the type of natural hazard. Although the existing dataset includes natechs triggered by various natural hazards, the number of incidents and their incident narratives are not sufficient to identify and describe all possible impact modes in detail. Some frequently observed damage and impact modes in the available natechs are listed below.

All failures related to the Northridge Earthquake in 1994, were ruptures and cracks in acetylene welds of a pipeline constructed in 1925. The failures are attributed to the welding method and inadequate construction standards of the time (NIST, 1997). In fact, two other pipelines exposed to the same earthquake forces in the epicentral area, which were constructed after 1950 with better welding methods (arc welding), did not sustain any damage. If earthquake risk is properly taken into consideration and modern industry standards are utilized during the construction, the seismic vulnerability of pipeline systems can be reduced significantly. For example, the Trans-Alaska Pipeline

System suffered only minor damage and no spill during the 2002 Denali Earthquake (MW 7.9) although the fault rupture crossed the pipeline within the 500 m corridor and shifted about 4 m horizontally and 0.75 m vertically (USGS, 2003).

Two natechs involving drought occurred in December, 1995 near Palo Pinto, Texas. Extended drought conditions allowed the ground to shift causing collar joint failures along the same pipeline at different dates.

Four different impact modes were identified for freeze-related natechs, which are frozen components (5%), falling ice/snow (8%), ice formation (13%), and ice expansion (74%). Falling ice/snow resulted in cracks at the pipeline components, whereas frozen components mostly caused component malfunction leading to releases. Ice formation was also found to have caused component malfunction and blockage of auxiliary pipes. Expansion of ice during freezing was the most prevalent impact mode and generally caused cracks in the components. Water naturally found in the transported substances is the main source of ice. Ice formation from residual water from hydro-testing of the pipeline system also caused several incidents.

The impact mode observed in all high wind natechs was debris impact (e.g. boards) carried by the winds or the falling of structures (e.g. power pole) due to excessive wind forces. Similar impact modes were also observed for tornados.

In case of winter storms, the observed impact mode was snow weight. In one of the incidents, the weight of the accumulated snow caused the floating roof of an aboveground storage tank to sink and in the other case it resulted in the failure of a fitting. The impact mode of rocks resting on pipelines was denting followed by pinhole leaks or hairline cracks resulting in spills.

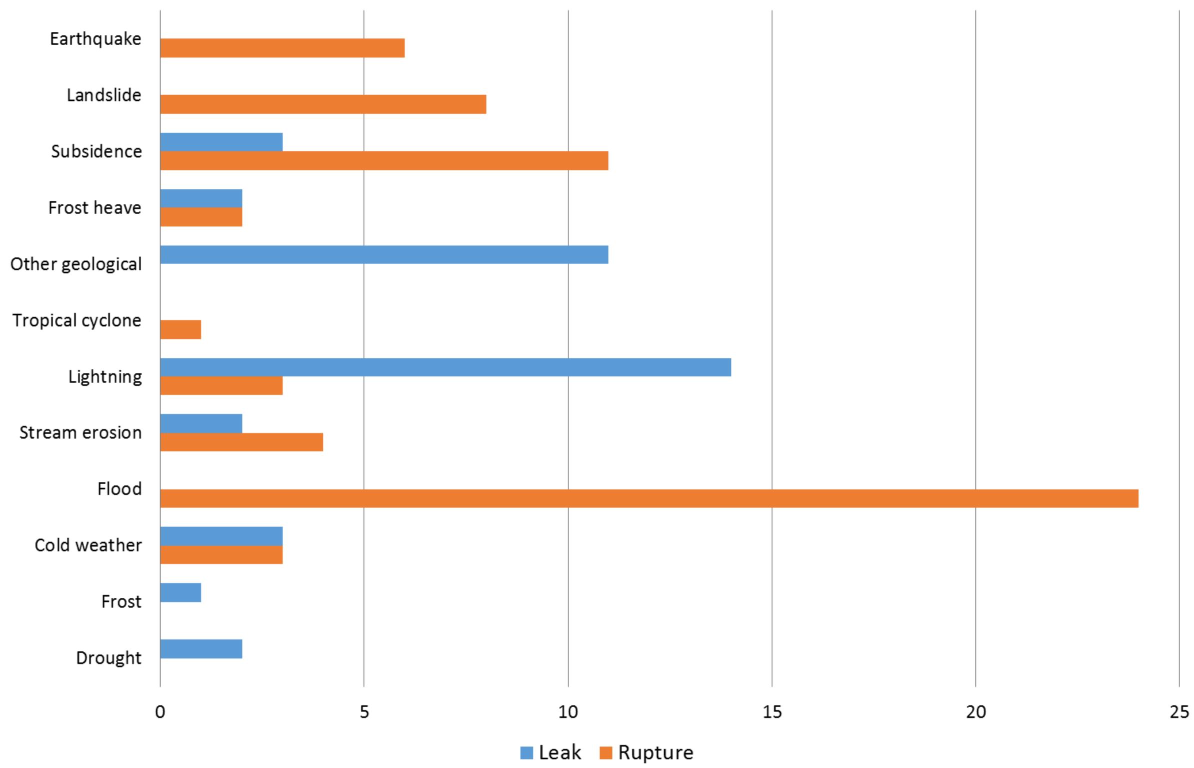


Figure 3.39. Distribution of pipe damage modes with respect to hazard

The analysis also confirmed the results of recent analyses of global natech accident data (including Europe and the USA) that highlighted the significant vulnerability of certain types of storage tanks to natural hazards and the associated safety and security risks. These studies found that atmospheric storage tanks, used for the storage of flammable hydrocarbons, are by far the most vulnerable equipment type at storage terminals. This finding is valid for earthquakes, floods and lightning (Krausmann et al., 2011). With tanks usually storing large quantities of material, the major accident potential is high. Significant damage to storage tanks was observed during past major earthquakes. These include, e.g., the 1999 Kocaeli earthquake which caused large fires at a refinery's naphtha storage tank farm (Girgin, 2011), or the fires that raged at a refinery in Tokyo Bay, after the 2011 Great East Japan earthquake (Krausmann and Cruz, 2013). Post-accident analysis covering a set of 79 earthquake-related Natechs found that the main damage and failure modes for earthquakes are buckling of the tank shell, deformation or failure of support structures, failure of flanges and tank-pipe connections, tank roof failure, or tank collapse and overturning (Krausmann et al., 2011; Campedel, 2008). Upon release of flammable substances, the ignition probability is high (0.76).

In the case of floods, failure of flanges and pipe connections, roof failure and/or shell rupture, tank floating or collapse were observed. Another important damage mechanism is impact with floating debris which can cause important releases (Krausmann et al., 2011; Cozzani et al., 2010).

Lightning is an important cause of tank fires although the consequences are mostly local. In most cases, the lightning strike ignites flammable vapours present near a tank (e.g. on the floating roof if the perimeter seal is not intact). If the lightning is sufficiently energetic it can melt the thin tank shell, exposing its contents. Lightning can also disrupt safety instrumentation, thereby indirectly leading to releases of hazardous materials (Renni et al., 2010; Krausmann et al., 2011).

Human Health

According to the available data, there were no fatalities due to natech incidents during the study period (1986-2012). 1,851 injured people were reported due to three pipe breaks during the San Jacinto River flooding near Harris, Texas on 20 October, 1994. However, the National Transportation Safety Board's incident investigation report indicates that the actual number is lower and a total number of 547 persons were treated at local hospitals, primarily for minor smoke and vapour inhalation complaints. Only 2 of the injuries were serious due to burn injuries (NTSB, 1996a). The high number of injured people was due to the significant amount of petroleum product that caught fire and moved downstream with the flooded stream flow. Most probably due to the discrepancy in the reported numbers, PHMSA excludes the total number of injured people from these events from the official summary statistics (PHMSA, 2014b). Although it was not numerically indicated in the incident data, the incident narrative of a petroleum condensate spill containing Mercaptan due to stream erosion/scouring that occurred on September 7, 1986, at the Red River crossing near Cooke, Texas, (Incident #19860145) mentions that there is information about the treatment of 14-15 persons at a hospital. Newspaper articles also support this information (Observer Reporter, 1986). A NIST report on the lifeline performance and post-earthquake response for the Northridge Earthquake mentions that the crude oil that spilled in the City of San Fernando into the Los Angeles River caught fire on its course along the river and injured one person (NIST, 1997). However, this injury is also not reported in the PHMSA data.

Fire and Explosion

There are 54 natech incidents which resulted in fire (23%). The majority of the fire incidents were due to lightning and the contribution of other natural hazards is comparatively insignificant. Lightning incidents also differ from other natechs with a high observed frequency of ignition. 78% of the lightning incidents resulted in fires as a consequence. The high ignition frequency related to lightning incidents is also observed in other pipeline network systems (EGIG, 2011). The occurrence of fires did not show any dependency with respect to substance type. However, they occurred more frequently at aboveground storage tanks (43%), followed by pipelines (32%). In addition to fires, explosions were also reported for 11 natech incidents. But the available associated incident narratives do not include any information related to the occurrence of explosions in more than 70% of these incidents. Natech incidents involving

4. Conclusions

Natural hazards can impact oil transmission pipelines with potentially adverse consequences on the population and the environment. They can also cause significant economic impacts to the pipeline operators due to potential reconstruction, clean-up and recovery actions that might be required and also due to possibly associated legal penalties. There is only limited historical information available on the dynamics of natural hazard impact on pipelines and Action A6 of the EPCIP 2012 Programme aims at shedding light on this issue.

This study focused on the collection and analysis of European and U.S. hazardous liquid and natural gas transmission pipeline incident data which were included into a specifically developed database-driven incident data analysis system. The analysis system and preliminary results of the incident data analysis were reported in the first year final report of the study. This report presents the findings of the second year of the study that focused on onshore hazardous liquid transmission pipeline natechs, with special emphasis on natural hazard impact and damage modes, incident consequences, and lessons learned for scenario building.

Due to the low number of incidents, the European incident data alone was not sufficient to identify natural-hazard specific impact and failure modes at the oil pipeline components and to develop representative natech scenarios. For this reason, data on U.S. pipeline natech incidents was included in this study. Although the dominating natural hazards vary due to geological and climatic differences, the additional use of U.S. data allowed a more complete analysis, the results of which are equally applicable to the European oil pipeline network for selected natural hazards.

Initially, the lack of publicly available detailed incident information for Europe was a limiting factor for the study, but it was mitigated by data made available recently by CONCAWE. Although the available information is still limited compared to the U.S. data, it allowed a more detailed incident analysis which showed that natechs constitute 4% of all reported oil and petroleum product pipeline incidents that occurred in Europe in the last four decades (1971-2012). The total number of reported natech incidents in Europe is 20, which results in a yearly natech occurrence rate of 0.5 incidents/year for a pipeline network of about 33,350 km (in 2012). Recent natechs are rare and there is only one pipeline natech incident since 1995. 90% of the natechs involve the pipe body, whereas the remainder involves pump stations. There are no reported natechs at intermediate storage facilities. All pipelines involving natech incidents were installed in the 1960s.

In Europe, geological hazards were the primary trigger of oil and petroleum product pipeline natechs with 65%, followed by hydrological and climatic hazards with 20% and 10%, respectively. Meteorological hazards played a minor role. The main incident initiators among geological hazards were landslides, which were mainly triggered by heavy rains. The remainder is mostly subsidence events primarily affecting not the pipe body but other pipe elements. The incident analysis highlights the occurrence of subsidence caused by coal mining activities, although the risk was a priori known to the operators. There is only one frost heave incident, and no earthquake related natech were found in the reported incidents. All hydrological incidents are related to floods. No other water-related hazards such as stream scouring under normal flow conditions was observed. Difficulties during the clean-up and recovery phases due to high and turbulent water conditions were common in these incidents. Although cold weather conditions are common in Europe, only hot weather related climatic natechs were reported, which were relatively minor incidents compared with other pipeline natechs. The total amount of crude oil and petroleum products released to the environment due to natech incidents was 6,000 m³, 40% of which was subsequently recovered. The median release volume was 120 m³ and at least half of the released amount was recovered in 75% of the incidents. The total estimated cost of the natech incidents at oil and petroleum product pipelines in Europe as corrected for inflation is about 40 million Euro. The highest cost for a single event is 14.4 million Euro while the median cost is 0.8 million Euro.

Similar to the European data, U.S. pipeline incident data provided by the U.S. Department of Transportation is also available for more than four decades since 1968. Incident-specific reports can be accessed publicly and provide detailed information especially for the recent incidents. However, due to data limitations and a change of reporting criteria with time, only incident data for a period of 25 years (1986-2012) was utilized for the study. Among the 6,976 onshore hazardous liquid pipeline incidents analysed for the study, 387 natechs were identified which corresponds to about 5.5% of all incidents for a network length of 300,000 km (in 2012).

The U.S. pipeline natech incident data showed that the vulnerability of the hazardous liquid pipeline network components varies significantly with natural hazard type and system part. Unlike in Europe, meteorological hazards were the main trigger, resulting in both the highest number of incidents and the highest total cost, which were around 40% and 60%, respectively. In terms of number, geological and climatic hazards were the other major hazards with about one quarter contribution each. However, climatic natechs resulted in less than 10% of the total release and their total cost was even more insignificant (2%). While hydrological hazard triggered incidents occurred less frequently than the other natech incidents, their consequences were significant and correspond to one third of the total release and overall cost. The analysis also showed that the susceptibility to natural hazards is not uniform among the different hazardous liquid pipeline network parts (e.g. pipe run, pumping/metering stations, and intermediate tank farms/terminals). All incidents related to hydrological hazards involved the main pipeline body, the same holds for incidents caused by geological hazards with more than 75%. However, in case of meteorological and climatic natechs, the distribution shifts towards incidents involving aboveground storage tanks. About 50% of meteorological and 40% of climatic natechs occurred at intermediate storage tanks, followed by pumping and metering stations with 21% and 24%, respectively. The total amount of hazardous substances released due to the natech incidents was about 50,875 m³ (320,000 barrels) resulting in 590 million USD economic damage.

The overall analysis showed that:

- **There is a tendency to underreport natural hazards as causes of incidents.** Although natural hazards are available explicitly as incident cause options in the incident reporting forms, incidents triggered by natural hazards are not always properly reported as natural-hazard related. The significant number of natech incidents additionally identified in both CONCAWE and PHMSA data sets during the peer-review process is an indicator of this situation. Although for some cases it is difficult and also technically demanding to correlate incidents to natural hazards, some misclassifications can be solved by proper guidance.

- **Although they occur less frequently, the consequences of natechs can be comparatively more significant than for other pipeline incidents.** For the PHMSA data, the total cost of natech incidents was found to be 19.4% of the total cost of all incidents although in terms of the number of incidents the contribution was only 7.2%. Hence, natechs resulted in more economic damage per incident compared to other incidents. Likewise, for the period, for which sufficient data was available, the average ratio of the number of significant natechs to the number of natechs due to all causes (45%) is considerably larger than the ratio of the incidents (33%). This suggests that natechs tend to be more severe events in terms of consequences compared to other incidents.

- **The natural hazard damage susceptibility of pipeline systems differs with system type.** Although this report focuses on oil pipeline systems, information collected in the first part of the study including natural gas pipeline systems shows that the damage susceptibility of pipeline systems for specific natural hazards is not the same for different system types. For example, historical incident data indicates that oil pipelines perform well in case of earthquakes, while many failures were observed for natural gas pipelines. A similar behaviour is also observed for some other natural hazards. A reason for this could be the changes in the geographic distribution and density of the different systems, but structural and operational differences also seem to be play a role.
- **Natural hazards do not impact all pipeline system parts equally and some parts are more and even sometimes only susceptible to selected types of natural hazards.** Pipeline systems do not only include the pipe run, but also various connected facilities such as valve sites, pumping/metering stations, intermediate storage units, and terminals. Most of these facilities are aboveground structures and contain a wide-range of components and equipment other than pipes. The analysis shows that underground pipelines are not susceptible to weather and climate related hazards, whereas aboveground facilities are more exposed to such hazards compared to geological and hydrological hazards. Damage modes are also significantly different for different system parts, especially if the impacted item is a component like a valve, pump, or control equipment. Therefore, while studying the natural hazard impact on pipeline systems, different system parts should be handled separately, especially if the study involves the historical analysis of incident data including economic losses and environmental consequences.
- **Impact mechanisms at pipeline system parts other than the pipe run are not specific to pipelines and are similar to their counterparts at fixed industrial plants.** Aboveground facilities of pipeline systems, especially intermediate aboveground storage tanks and terminals, and similar facilities at fixed industrial plants, e.g. refineries, have common design and components. Therefore the natech susceptibility and observed natech-related damage modes are also not different as indicated by the study. Instead of or in addition to analysing data originating from pipeline systems, which is limited in extent, incident data from fixed industrial plants, which is more widely available, can be used to obtain more and accurate information for such parts. Existing industrial accident databases and the scientific literature can be utilized for this purpose.
- **Earthquakes are perceived to be a major threat to pipelines but historical data shows that they have not or very rarely triggered natech incidents in hazardous liquid transmission pipelines.** No related incidents were reported in Europe and there is only one triggering earthquake in the U.S., which affected a single and specific kind of pipeline, over a period of 40 years. Well established design criteria, proper construction methods, and appropriate protection measures are presumably the reasons for the good earthquake performance.
- **Besides directly triggering incidents, natural hazards can also aggravate other incidents by accelerating causes, facilitating transport of spilled substances, or hindering response and recovery operations.** Although the study focused on pipeline incidents triggered by natural hazards, the analysis also showed that natural hazards can accelerate the occurrence of incidents

due to other primary causes (e.g. corrosion due to natural hazard effects), and facilitate or even initiate the transport of material spilled due to incidents caused by other reasons, which would otherwise stay contained in a small area (e.g. rain sweep of released substances). Natural hazard condition can also hinder or complicate response, recovery, and clean-up operations, which could otherwise happen quickly. Especially major natural disasters, such as earthquakes and tropical cyclones, may result in competing resource needs. These aggravating factors should also be considered while assessing natural hazard impacts on pipeline systems.

- **Slow onset hazards and the variation in time of some natural hazards should be considered during the design and operation of pipeline systems, which typically have a very long operational life.** Most of the hazardous liquid pipelines in Europe were built in 1960-1970 and about 60% of the operational pipelines are currently older than 40 years. In the U.S., there are operational pipelines which were built over 100 years ago. Even if natural hazard risks were considered at the time of the design and construction of the pipelines, changes in the regional natural hazard risks are very likely due to the large geographical extent of the pipeline systems and also global factors, such as climate change. For example, the severity of a 100-year design flood may change over time, resulting in an under-protection of the pipeline system and posing unprepared-for risks, e.g. at river crossings. Along the same lines, earthquakes might change the geological boundary conditions in an area, thereby potentially affecting fault line parameters and hence the severity of earthquakes to come. The possible time variation of natural hazards should be considered during the operational life of the pipelines, and risks and associated mitigation measures should be periodically reviewed. This process should be regulated by competent authorities, especially for pipelines located in high natural-hazard risk zones.

- **Regulatory measures for the construction and operation of pipeline systems that consider possible time-varying natural hazard risks and impose comprehensive reporting obligations are necessary for the proper prevention and mitigation of pipeline natechs.** Currently, there is no comprehensive EU legislation on pipeline safety. The construction and operation of pipelines are regulated by national legislation in the Member States. A recent study assessing the case for EU legislation on the safety of pipelines shows that although there are no major gaps in the legislative coverage of national regulations, deficiencies exist in various topics such as emergency planning and information to the public (COWI, 2011). However, no specific information is available about whether or not possible impacts of natural hazards are adequately considered in national regulations or what national pipeline accident reporting obligations are. There is also no EU-wide directive for reporting of pipeline accidents. EU directive 2012/18/EU on the control of major-accident hazards involving dangerous substances (Seveso III Directive) and previous directives repealed thereby, explicitly exclude pipelines transporting dangerous substances beyond the boundaries of establishments covered by the directive (EU, 2012). Therefore, oil and gas transmission pipelines are not covered. In contrast, in the U.S., a federal law on pipeline safety (49 CFR Parts 186-199) regulates both hazardous liquid and natural gas pipelines by defining rules for topics such as system and incident reporting, design requirements, construction, pressure testing, operation and maintenance, and corrosion control. There is also a comprehensive incident data reporting system managed by a single governmental organization (PHMSA) both for hazardous liquid and natural gas pipelines.

- **Detailed incident and natural hazard data should be made available for the proper analysis of pipeline natech incidents, especially for regional or global studies.** Currently, Europe-wide pipeline accident data is collected only by non-governmental organisations established by oil and gas companies. In case of oil pipelines, CONCAWE has been collecting data on the safety and environmental performance of the pipelines via questionnaires sent to pipeline operators for more than 40 years. The results of their analyses were published as annual detailed and 5-yearly summary reports, which are publicly available. EGIG has been doing the same for the gas transmission pipelines for a similar time period, and is periodically publishing summary reports about the safety performance. Although some notable pipelines are not covered (e.g. NATO lines in selected European countries), the overall geographical reporting coverage of both the organizations is high and also representative for Europe. However, publicly available data is limited and also restricted. While EGIG does not provide any incident-specific information at all, CONCAWE is keeping the location and the date of the incidents confidential. However, for natural-hazard related studies location information is also crucial because natural hazards are location dependent and to evaluate natural hazard impact mechanisms and the associated future risk location needs to be known. It should also be noted that, although CONCAWE and EGIG are successful in collecting incident data for a long period, data reporting itself is not compulsory and hence highly dependent on the goodwill of the operators. Hence it cannot be guaranteed that all pipeline incidents are actually reported and it is also not certain that they are accurately reflecting the real conditions. This situation highlights the need for a concerted and statutory effort in collecting European pipeline incident data both for hazardous liquid and natural gas transportation, and its dissemination for safety and lessons learning purposes. This information should include detailed information on the incident trigger (with special emphasis on the type and the severity of the natural hazard for natechs), damage or failure modes, consequences of the incident, and an assessment of the performance of prevention and mitigation measures. Near misses should also be included in the data collection where possible as these incidents can teach important lessons on the successful performance of safety systems. Although some deficiencies exist as highlighted by this study, PHMSA collects detailed incident data from hazardous liquid and natural gas pipeline operators in the U.S. Besides statistical summaries, incident-specific detailed information is publicly available.
- **Besides data availability, data quality and explicit data limitations are equally important and should be carefully evaluated during the analysis.** Although incident data is often available for long time periods, varying reporting criteria or different reporting formats can create a significant bias in the data that needs to be considered in the analysis. Although termed similarly, definitions of data fields can be significantly different for different periods or changes in the reporting criteria may influence implicitly their definition preventing clustering or aggregation. Ambiguities in the total cost data of the PHMSA incidents due to changes in the PHMSA reporting criteria and reporting formats is an example of this problem.
- **Pipeline operators should periodically update and complete incident reports if previously unknown or more accurate information becomes available, and competent authorities should encourage and actively follow this process.** Certain types of incident information, such as environmental consequences and economic costs, cannot be assessed quickly. In the case of natechs, unusual conditions due to the triggering natural hazard may even hinder the collection of basic information. Incomplete or outdated information is difficult to recognize by third parties,

hence it cannot be filtered out easily from the analysis and may result in erroneous conclusions. Data actuality and completeness is crucial for a proper analysis and should be assured by all responsible parties. Cost estimates in the PHMSA data, which are significantly under-estimated, are an example.

- **In order to support the lessons learning process, operators should be encouraged to also share information on near misses or incidents below the reporting threshold.** For the business continuity and the prevention of similar future incidents, pipeline operators are collecting detailed information not only about critical events, but also near-misses and below reporting-threshold incidents. The actual values of parameters that are otherwise difficult to obtain, such as clean-up and recovery costs, are also known by the operators with high accuracy. The sharing of this data would greatly enrich the data pool for lessons learning studies. It should be noted that for some incidents, this can actually be the only way to obtain valid information, because it may not be available elsewhere.

For this study, a database-driven incident data analysis system was developed to rapidly review, categorise, and query incident records according to their causes and consequences, and link them to related supplementary data. The system provides an automated pre-selection of incidents of potential interest using data mining methods. This can be supplemented by an expert review for manual confirmation of data accuracy, which can be carried out by multiple experts simultaneously.

During the study, European and U.S. incident and natural hazard data sources were reviewed, relevant data was collected, and imported into the study database. Using an automated data-mining process followed by a peer-review of the identified records, the pipeline natechs were identified. As a result, about 1,400 fully reviewed and categorised oil and natural gas transmission pipeline natech records are included in the study database. Similarly, approximately 2,150 natural gas distribution incidents were also identified as possible natechs and are ready for more detailed peer-review. In addition to onshore incidents, all data sets include offshore incidents, as well. Therefore, the occurrence mechanisms and consequences of offshore pipeline natechs can be studied. As a by-product of the data collection process, the database furthermore includes over 800,000 U.S. National Response Centre incident reports from all causes in industrial and transportation activities, which are automatically classified in the same way as the pipeline incident records. The database is available for future studies and is especially useful for providing case-specific natech data, which is scarce in the scientific literature and in the existing accident databases.

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Appendix A. Natural Hazard Definitions

A.1. Geological Hazards

Earthquake is the result of a sudden release of energy in the Earth's crust that creates seismic waves. At the Earth's surface, earthquakes manifest themselves by shaking and sometimes displacement of the ground. Earthquakes can also trigger landslides, and occasionally volcanic activity.

Landslide is a geological phenomenon which includes a wide range of ground movement, such as rock falls, deep failure of slopes and shallow debris flows, which can occur in offshore, coastal and onshore environments. Although the action of gravity is the primary driving force for a landslide to occur, there are other contributing factors affecting the original slope stability.

Mudslide is a rapid movement of a large mass of mud formed from loose soil and water. Mudslides are caused by unusually heavy rain or a sudden thaw. They consist mainly of mud and water plus fragments of rock and other debris; this causes them to behave like a flood.

Debris flow is fast moving, liquefied landslides of mixed and unconsolidated water and debris that look like flowing concrete. They are differentiated from mudflows by their coarser and more poorly sorted sediment load. Flows can carry material ranging in size from clay to boulders, and may contain a large amount of woody debris such as logs and tree stumps.

Subsidence is the motion of the Earth's surface as it shifts downward to a datum such as sea-level.

Frost heave results from ice forming beneath the surface of soil during freezing conditions in the atmosphere. The ice grows in the direction of heat loss (vertically toward the surface), starting at the freezing front or boundary in the soil. The growing ice is restrained by overlying soil, which applies a load that limits its vertical growth and promotes the formation of a lens-shaped area of ice within the soil. The force of one or more ice lenses is sufficient to lift a layer of soil, as much as 30 cm or more.

Rock fall is a fragment of rock (a block) detached by sliding, toppling, or falling, that falls along a vertical or sub-vertical cliff, proceeds down slope by bouncing and flying along ballistic trajectories or by rolling on talus or debris slopes.

Rockslide is a type of landslide caused by rock failure in which part of the plane of failure passes through intact rock and where material collapses en masse and not in individual blocks. The rocks tumble downhill loosening other rocks on its way also smashing everything in its path. The mode of failure is different from that of a rock fall.

Avalanche is a rapid flow of snow down a slope. Although primarily composed of flowing snow and air, large avalanches have the capability to entrain ice, rocks, trees, and other material on the slope, and are distinct from mudslides, rock slides, and serac collapses on an icefall.

Soil erosion is the process by which soil and rock are removed from the Earth's surface by exogenic processes such as wind or water flow, and then transported and deposited in other locations. Excessive erosion, increased by human activities, causes problems such as desertification, decreases in agricultural productivity due to land degradation, sedimentation of waterways, and ecological collapse due to loss of the nutrient rich upper soil layers.

Volcanic eruption is expulsion of lava, tephra (ash, lapilli, volcanic bombs and blocks), and various gases from a volcanic vent or fissure. A volcanic eruption can be driven by the decompression or compression of gas within magma, or by the super-heating of steam via contact with magma.

A.2. Hydrological Hazards

Flooding is an overflow of water from water bodies, such as a river or lake, in which the water over tops or breaks embankments, resulting in some of that water escaping its usual boundaries.

Flash flooding is a rapid flooding of geomorphic low-lying areas: washes, rivers, dry lakes and basins due to heavy rains, melt-water from ice or snowfields, or collapse of natural or human-made dams.

Stream erosion occurs with continued water flow along a linear feature. The erosion is both downward, deepening the valley, and head ward extending the valley into the hillside, creating head cuts and steep banks. Bank erosion is the wearing away of the banks of a stream or river. This is distinguished from changes on the bed of the watercourse, which is referred to as scour.

Storm surge is an offshore rise of water associated with a low pressure system, typically tropical cyclones and strong extra-tropical cyclones. It also refers to storm tide, which is the rise of water associated with the storm, plus tide, wave run-up, and freshwater flooding.

Tsunami is a series of water waves caused by the displacement of a large volume of a body of water, generally an ocean or a large lake. Rather than appearing as a breaking wave, a tsunami may instead initially resemble a rapidly rising tide, and for this reason they are often referred to as tidal waves or harbour waves.

A.3. Meteorological Hazards

High wind is a very strong wind with speeds exceeding 50 km/h.

Heavy rainfall is a rain having a precipitation rate greater than 10 millimetres per hour. It may result in an areal flood due to an accumulation of rainwater on saturated ground.

Storm is any disturbed state of an astronomical body's atmosphere especially affecting its surface, and strongly implying severe weather. It may be marked by strong wind, hail, thunder and/or lightning (a thunderstorm), heavy precipitation (snowstorm, rainstorm), heavy freezing rain (ice storm), strong winds (tropical cyclone, wind storm), or wind transporting some substance through the atmosphere as in a dust storm, blizzard, sandstorm, etc.

Winter storm is an event in which the varieties of precipitation are formed that only occur at low temperatures, such as snow or sleet, or a rainstorm where ground temperatures are low enough to allow ice to form.

Ice storm is a type of winter storm characterized by freezing rain, also known as a glaze event or a silver thaw. The U.S. National Weather Service defines an ice storm as a storm which results in the accumulation of at least 0.25-inch (6.4 mm) of ice on exposed surfaces.

Hail is a form of solid precipitation consisting of balls or irregular lumps of ice, each of which is called a hailstone. Hailstones consist mostly of water ice and measure between 5 millimetres and 15 centimetres in diameter.

Tornado (twister, cyclone) is a violently rotating column of air that is in contact with both the surface of the earth and a cumulonimbus cloud or, in rare cases, the base of a cumulus cloud. They are typically in the form of a visible condensation funnel, whose narrow end touches the earth and is often encircled by a cloud of debris and dust.

Tropical cyclone (hurricane, typhoon, tropical depression) is a rapidly-rotating storm system characterized by a low-pressure centre, strong winds, and a spiral arrangement of thunderstorms that produce heavy rain. They typically form over large bodies of relatively warm water and, in addition to strong winds and rain, are capable of generating high waves, damaging storm surge, and tornadoes.

Extratropical cyclone (mid-latitude cyclone, wave cyclone) is defined as synoptic scale low pressure weather system that occurs in the middle latitudes (outside the tropics) not having tropical characteristics, and is connected with fronts and horizontal gradients in temperature and dew point. Extratropical cyclones are the everyday phenomena which, along with anticyclones, drive the weather, producing anything from cloudiness and mild showers to heavy gales and thunderstorms.

Lightning is a massive electrostatic discharge between electrically charged regions within clouds, or between a cloud and the Earth's surface. Lightning primarily occurs when warm air is mixed with colder air masses resulting in atmospheric disturbances necessary for polarizing the atmosphere.

A.4. Climatic Hazards

Cold weather is a period of unusually cold weather

Hot weather (heat wave) is a prolonged period of excessively warm weather, which may be accompanied by high humidity. While definitions vary, a heat wave is measured relative to the usual weather in the area and relative to normal temperatures for the season. Severe heat waves have caused catastrophic crop failures, thousands of deaths from hyperthermia, and widespread power outages due to increased use of air conditioning.

Drought is an extended period of months or years when a region notes a deficiency in its water supply whether surface or underground water. Generally, this occurs when a region receives consistently below average precipitation.

Wild fire is an uncontrolled fire in an area of combustible vegetation that occurs in the countryside or a wilderness area. A wildfire differs from other fires by its extensive size, the speed at which it can spread out from its original source, its potential to change direction unexpectedly, and its ability to jump gaps such as roads, rivers and fire breaks. It is also termed as brush fire, bushfire, forest fire, desert fire, grass fire, hill fire, and vegetation fire.

Appendix B. PHMSA Natech Incident Data

Summary data for 387 PHMSA onshore hazardous liquid pipeline natech incidents identified in the study are given in this appendix. Basic information about the date, location, pipeline system and involved item, natural hazard impact and damage modes, and consequences are provided. More detailed information for each incident is available in the study database, which is accessible through the data analysis system developed for the study.

For convenience, the natech incidents are grouped under subsections divided by the natural hazard categories, i.e. geological, hydrological, meteorological, and climatic. Incidents triggered by each natural hazard are listed in a separate table as ordered by significance and occurrence date.

Table B.1. PHMSA natech incident data column descriptions

Data Column	Description
Significance	Significant incidents fulfilling the criteria listed in Section 3 (page 25) are indicated with a bullet (•) in the first column.
Date	Incident date
Location	Incident location by U.S. state and county
Substance	Substance involved: Crude Oil — Crude oil HVL — Substances which are liquid at ambient conditions non-HVL — Substances which are gas at ambient conditions CO_2 — Carbon dioxide
System Part	System part involved: PL — Pipeline PVS — Pipeline valve site AST — Aboveground storage tank PMS — Pumping/metering station TTF — Terminal/tank farm
System Item Location	Location of the involved system item: ▬ Belowground ▲ Aboveground
System Item	System item involved to the incident. If sufficient information is available, the sequence of the parent items is indicated for incidents that are part of a unit or equipment.
Pipe Diameter	Diameter of the pipe for incidents involving the pipe body
Impact and Damage Modes	Natural hazard impact and damage modes. Impact and damage modes are separated by a double angle quotation mark (») and they are provided as event sequences, if sufficient information is available.
Medium	Release medium: Air — Atmosphere Land — Soil, Dike, Secondary containment, and wetland Water — Stream, river, channel, pond, lake, and estuary None — No external release to the environment (e.g. consumed by fire)
Spill Quantity	Amount of spilled substance in barrels (BBL) (1 BBL ≈ 159 L)
Economic Cost	Total cost of the incident in USD as adjusted to the inflation by using the 2010 GDP price indices for 2013 (rounded to nearest thousand) (BEA, 2010).

A.1. Geological Natechs

Earthquake

	Date	Location	Substance	System Part	Grd	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1994-01-17	Los Angeles, CA	Crude Oil	PL	▬	Girth Weld	10"	Northridge Earthquake » Weld failure (Rupture)	-	Soil	35	146,000
●	1994-01-17	Los Angeles, CA	Crude Oil	PL	▬	Girth Weld	10"	Northridge Earthquake » Weld failure (Rupture)	-	Soil	592	160,000
●	1994-01-17	Los Angeles, CA	Crude Oil	PL	▬	Girth Weld	10"	Northridge Earthquake » Weld failure (Rupture)	-	Water	4,207	17,516,000
●	1994-01-17	Los Angeles, CA	Crude Oil	PL	▬	Girth Weld	10"	Northridge Earthquake » Weld failure (Rupture)	-	Soil	183	147,000
●	1994-01-17	Los Angeles, CA	Crude Oil	PL	▬	Girth Weld	10"	Northridge Earthquake » Weld failure (Rupture)	-	Soil	561	2,335,000
●	1994-01-17	Los Angeles, CA	Crude Oil	PL	▬	Girth Weld	10"	Northridge Earthquake » Weld failure (Rupture)	●	Soil	561	2,335,000
	1994-01-17	Los Angeles, CA	Crude Oil	PL	▬	Girth Weld	10"	Northridge Earthquake » Weld failure (Rupture)	-	Soil	5	73,000
	1994-01-17	Los Angeles, CA	Crude Oil	PL	▬	Girth Weld	10"	Northridge Earthquake » Weld failure (Rupture)	-	Soil	-	13,000
	1994-02-23	Los Angeles, CA	Crude Oil	PL	▬	Girth Weld	10"	Northridge Earthquake » Weld failure (Rupture)	-	Soil	4	29,000
	1994-03-14	Los Angeles, CA	Crude Oil	PL	▬	Girth Weld	10"	Northridge Earthquake » Weld failure (Rupture)	-	Soil	< 1	15,000
	1994-03-24	Los Angeles, CA	Crude Oil	PL	▬	Girth Weld	10"	Northridge Earthquake » Weld failure (Leak)	-	Soil	1	36,000
	1994-03-30	Los Angeles, CA	Crude Oil	PL	▬	Girth Weld	10"	Northridge Earthquake » Weld failure (Leak)	-	Soil	1	16,000
	1994-03-30	Los Angeles, CA	Crude Oil	PL	▬	Girth Weld	10"	Northridge Earthquake » Weld failure (Rupture)	-	Soil	30	73,000

Landslide

	Date	Location	Substance	System Part	Grd	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1987-04-21	Jackson, MO	Non-HVL	PL	▬	Pipe	8"	Heavy rain > Landslide » Pipe failure (Rupture)	-	Soil	590	45,000
●	1990-03-30	Armstrong, PA	Non-HVL	PL	▬	Pipe	10"	Landslide » Pipe failure (Rupture)	-	Water	1,800	19,463,000
●	1997-06-20	Big Horn, MT	Non-HVL	PL	▬	Pipe	8"	Landslide > Over-stress » Pipe failure (Rupture)	-	Water	1,612	1,241,000
●	1997-06-26	Sheridan, WY	Non-HVL	PL	▬	Pipe	8"	Landslide > Over-stress » Pipe failure (Rupture)	-	Water	704	689,000
●	1998-02-14	Ventura, CA	Crude Oil	PL	▬	Pipe	10"	Heavy rain > Landslide » Pipe failure (Rupture)	-	Soil	249	1,422,000
●	1998-02-14	Ventura, CA	Crude Oil	PL	▬	Pipe	8"	Heavy rain > Landslide > Over-stress » Pipe failure (Rupture)	-	Water	111	14,000
●	2005-03-23	Los Angeles, CA	Crude Oil	PL	▬	Pipe	14"	Heavy rain > Landslide » Pipe failure (Rupture)	-	Water	3,393	15,786,000
●	2009-05-12	Miami, KS	HVL	PL	▬	Girth Weld	8"	Heavy rain > Landslide > Over-stress » Weld failure (Rupture)	-	Air	1,718	136,000
	1996-03-23	Cowlitz, WA	Non-HVL	PL	▬	Pipe	14"	Heavy rain > Landslide » Unknown (Leak)	-	Water	-	11,000

Subsidence

	Date	Location	Substance	System Part	Grd	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1986-12-26	Kern, CA	Crude Oil	PL	▬	Girth Weld	10"	Subsidence » Weld failure (Rupture)	-	Soil	380	65,000
●	1987-06-29	Garfield, CO	HVL	PL	▬	Pipe	10"	Ground shift » Pipe failure (Rupture)	-	Air	10,000	< 1,000
●	1988-01-03	Lincoln, OK	Crude Oil	PL	▬	Pipe	8"	Subsidence » Pipe failure	-	Soil	350	7,000
●	1991-10-03	McLean, KY	Non-HVL	PL	▬	Pipe	8"	River bank subsidence » Weld failure (Rupture)	-	Water	1,800	313,000
●	1991-10-30	Ascension, LA	HVL	PMS	▲	Meter Run > Fitting (1/2")	-	Excavation slide > External impact (conduit) » Fitting failure (Leak)	-	Air	37	5,000
●	1991-10-30	Refugio, TX	Crude Oil	PL	▬	Girth Weld	16"	Heavy rain > Subsidence » Weld failure (Rupture)	-	Soil	1,150	469,000
●	1993-01-21	Cotton, OK	Crude Oil	PL	▬	Collar	8"	Heavy rain > Ground shift » Collar failure (Leak)	-	Water	1,200	149,000
●	1993-02-16	Harris, TX	Non-HVL	PMS	▬	Pipe > Collar	12"	Subsidence » Collar failure (Leak)	-	Soil	80	14,000
●	1993-12-01	Franklin, MO	Non-HVL	PL	▬	Girth Weld	10"	Areal flooding > Subsidence » Weld failure (Rupture)	-	Water	200	89,000
●	1995-08-17	McPherson, KS	HVL	BGS	▬	Brine Line (8")	-	Shale ledge collapse » Piping failure	-	Air	10	4,000
●	1997-05-12	Refugio, TX	Crude Oil	PL	▬	Girth Weld	12"	Ground shift » Weld failure (Rupture)	-	Soil	1,800	69,000
●	2000-02-03	Navarro, TX	Crude Oil	PVS	▬	Valve > Flange (Bolted)	-	Subsidence » Flange failure	-	Soil	4,000	304,000
●	2002-04-29	Pottawatomie, OK	Crude Oil	PMS	▬	Tapped Flange > Nipple (1/2", Threaded)	-	Subsidence » Nipple failure	-	Soil	75	269,000
●	2004-01-24	Jefferson, TX	Crude Oil	PL	▬	Girth Weld	10"	Heavy rain > Ground shift » Weld failure (Rupture)	-	Soil	75	28,000
●	2004-08-15	Kern, CA	Crude Oil	PL	▬	Pipe	12"	Subsidence » Pipe failure (Rupture)	-	Soil	1,275	422,000
●	2005-01-26	Owen, KY	Crude Oil	PL	▬	Girth Weld	22"	Flooding > Subsidence » Weld failure (Rupture)	-	Water	6,909	9,939,000
●	2007-08-02	Ector, TX	Crude Oil	PL	▬	Collar	4"	Heavy rain > Subsidence » Collar failure (Leak)	-	Soil	600	103,000
●	2007-11-26	Harris, TX	Crude Oil	TTF	▬	Bend > Fitting (Welded)	24"	Subsidence » Weld failure (Leak)	-	Soil	3	158,000
●	2008-05-07	Hardin, TX	Crude Oil	PL	▬	Pipe	4"	Sinkhole » Pipe failure (Rupture)	-	Soil	10	108,000
●	2010-03-30	Chariton, MO	HVL	PL	▬	Pipe	8"	Downhill soil settlement » Pipe failure (Leak)	-	Air	656	116,000
●	2011-12-27	Loving, TX	HVL	PL	▬	Girth Weld	8"	Sinkhole? » Weld failure (Rupture)	-	Air	3,283	225,000
●	2012-10-07	Lafourche, LA	Crude Oil	AST	▲	Tank > Floor	-	Soil settlement » Tank floor failure	-	Soil	60	178,000
	1988-03-23	Cass, MO	Crude Oil	AST	▲	Tank > Gate Valve	-	Subsidence » Valve failure	-	Water	1	-
	1990-03-02	Adams, MS	Crude Oil	PL	▬	Pipe	8"	River bank subsidence? » Unknown (Leak)	-	Water	15	8,000
	2005-08-21	Shelby, AL	Non-HVL	AST	▲	Tank > Water Draw Line > Flange	-	Subsidence » Tank settlement > Flange failure	-	Soil	9	29,000

Frost heave

	Date	Location	Substance	System Part	Grd	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1988-08-23	Hennepin, MN	Non-HVL	PL	▬	Pipe	8"	Frost heave > Rock movement (concrete rubble) > Resting rock » Dent crack (Leak)	-	Soil	136	175,000
●	1990-02-26	Cook, IL	Non-HVL	AST	▲	Tank > Pump > Piping (10") > Flange (Bolted)	-	Frost heave » Flange failure (Leak)	-	Soil	325	22,000
●	1991-01-15	Whatcom, WA	Crude Oil	PMS	▬	Instrumentation Line (1")	-	Frost heave? » Piping failure	-	Soil	75	352,000
●	1994-01-21	Miami, KS	Non-HVL	PL	▬	Girth Weld	8"	Frost heave » Weld failure (Rupture)	-	Water	3,869	3,443,000
●	1994-04-09	Dawson, MT	Crude Oil	PMS	▲	Scraper Trap Relief > Piping (1")	-	Frost heave » Piping failure	-	Soil	1,100	7,000
●	1998-12-28	Carter, MT	Crude Oil	PMS	▲	Piping > Nipple (Threaded)	-	Frost heave » Nipple failure	-	Soil	190	82,000
●	1999-01-16	Douglas, WI	HVL	TTF	▲	Instrumentation Line (3/4")	-	Frost heave » Piping failure	●	Air	130	491,000
●	2000-11-19	Williams, ND	CO_2	PVS	▬	Valve	-	Frost heave » Valve failure	-	Air	83	489,000
●	2001-04-01	Bottineau, ND	HVL	PL	▬	Pipe	12"	Frost heave » Pipe failure (Rupture)	●	Air	27,660	1,139,000
●	2001-04-17	Monroe, MI	Non-HVL	PVS	▬	Valve > Fitting	-	Frost heave » Fitting failure	-	Soil	5	142,000
●	2003-03-16	Clearwater, MN	Crude Oil	TTF	▬	Transfer Line > Nipple (3/4", Threaded)	-	Frost heave » Nipple failure	-	Soil	1	109,000
●	2003-05-17	Cumberland, ME	Crude Oil	PL	▬	Pipe	24"	Frost heave > Rock movement (boulder) > Resting rock » Dent crack (pinhole) (Leak)	-	Soil	12	254,000
●	2004-01-25	Delaware, NY	HVL	PVS	▬	Tap	-	Frost heave » Tap failure	●	Air	6,200	375,000
●	2007-02-18	Allen, OH	Non-HVL	PMS	▬	Injection Line (1") > Elbow Joint	-	Frost heave » Joint failure	-	Soil	50	59,000
●	2007-02-23	Will, IL	HVL	PMS	▲	Transmitter > Intelligence Line > Fitting (1/2")	-	Frost heave » Fitting failure	-	Air	10	2,000
●	2008-03-23	Clearwater, MN	Crude Oil	AST	▲	Tank > Piping (6")	-	Frost heave » Piping failure	-	Soil	1,600	519,000
●	2012-03-22	Clearwater, MN	Crude Oil	TTF	▬	Valve > Piping	-	Frost heave » Piping failure	-	Soil	< 1	102,000
	1994-02-08	Dauphin, PA	Non-HVL	AST	▲	Tank > Manifold > Thermal Relief Line (1/2") > Nipple (Threaded)	-	Frost heave » Nipple failure	-	Soil	15	22,000
	1994-05-24	Essex, VT	Crude Oil	PL	▬	Pipe	24"	Substandard backfill + Frost heave > Rock movement (boulder) > Resting rock » Dent crack (Leak)	-	Soil	1	73,000
	2003-06-23	Essex, VT	Crude Oil	PL	▬	Pipe	24"	Frost heave > Rock movement (boulder) > Resting rock » Dent crack (pinhole) (Leak)	-	Soil	1	93,000
	2007-02-05	Clearwater, MN	Crude Oil	TTF	▬	Pressure Control Valve > Fitting (1/2")	-	Frost heave » Fitting failure	-	Soil	7	54,000
	2007-03-22	Clearwater, MN	Crude Oil	PMS	▲	Densitometer > Piping (2") > Union	-	Frost heave » Union failure	-	Soil	5	33,000
	2008-02-17	Ramsey, MN	Non-HVL	AST	▲	Tank > Pump > Base	-	Frost heave » Pump failure	-	Soil	6	62,000
	2009-02-01	Ramsey, MN	Non-HVL	AST	▲	Tank > Pump > Flange	-	Frost heave » Flange failure	-	Soil	21	66,000

Date	Location	Substance	System Part	Grd	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
2009-02-08	Boone, KY	Crude Oil	PMS	▬	Sump Discharge Line (2") > Joint (Threaded)	-	Frost heave » Joint failure	-	Soil	8	36,000
2010-01-06	Douglas, WI	Crude Oil	TTF	▬	Crossover Valve > Piping	-	Frost heave » Piping failure	-	Soil	< 1	12,000
2010-01-19	Madison, IL	Non-HVL	TTF	▬	Pressure Transmitter Line (1/2") > Joint (Threaded)	-	Frost heave » Joint failure	-	Soil	3	48,000
2010-02-04	Milwaukee, WI	Non-HVL	TTF	▲	Prover > Piping > Nipple	-	Frost heave » Nipple failure	-	Soil	< 1	5,000
2010-03-11	Douglas, WI	Crude Oil	AST	▬	Tank > Valve > Piping	-	Frost heave » Piping failure	-	Soil	< 1	8,000
2010-04-08	Pettis, MO	Non-HVL	PVS	▲	Valve > Bleeder > Nipple	-	Frost heave » Nipple failure (Leak)	-	Soil	< 1	< 1,000
2011-08-17	Douglas, WI	Crude Oil	AST	▬	Tank > Terminal Gate Valve > Piping > Nipple	-	Frost heave » Nipple failure (Leak)	-	Soil	< 1	84,000

Other geological

	Date	Location	Substance	System Part	Grd.	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1989-04-09	St. Louis, MN	Crude Oil	PL	▬	Pipe	26"	Resting rock » Dent crack (hairline, 4") (Leak)	-	Soil	100	118,000
●	1992-10-09	Henry, VA	Non-HVL	PL	▬	Pipe	8"	Resting rock » Dent crack (hairline, 1") (Leak)	-	Water	95	69,000
●	1994-11-01	Fannin, TX	Non-HVL	PL	▬	Pipe	28"	Resting rock » Dent crack (Leak)	-	Water	113	438,000
●	1995-01-04	Fayette, KY	Crude Oil	PL	▬	Pipe	24"	Substandard backfill > Resting rock » Dent crack (Leak)	-	Soil	27	179,000
●	1995-05-03	Henry, VA	Non-HVL	PL	▬	Pipe	8"	Resting rock » Dent crack (hairline, 2" + pinhole) (Leak)	-	Water	5	114,000
●	1998-05-21	Berks, PA	Non-HVL	PL	▬	Pipe	24"	Resting rock? » Dent crack? (Leak)	-	Water	1	139,000
●	1999-11-02	Ingham, MI	HVL	PL	▬	Pipe	30"	Resting rock » Dent crack (hairline, 4-5") (Leak)	●	Air	5,300	336,000
●	2001-03-02	Douglas, GA	Non-HVL	PL	▬	Pipe	26"	Resting rock » Dent crack (hairline, 8") (Leak)	●	Soil	87	901,000
●	2004-02-19	Itasca, MN	Crude Oil	PL	▬	Pipe	26"	Resting rock » Dent crack (pinhole) (Leak)	-	Soil	1,003	1,315,000
●	2010-06-08	Wood, WI	Crude Oil	PL	▬	Pipe	34"	Resting rock » Dent crack (Leak)	-	Soil	1	346,000
●	2010-11-12	Scott, MN	Non-HVL	PL	▬	Pipe	12"	Resting rock » Dent crack (Leak)	-	Water	48	413,000
	1986-10-29	Pittsylvania, VA	Non-HVL	PL	▬	Pipe	32"	Resting rock » Hole (1/8") (Leak)	-	Water	12	18,000
	1989-06-26	Talladega, AL	Non-HVL	PL	▬	Pipe	30"	Resting rock » Dent crack (Leak)	-	Soil	1	20,000
	1989-06-29	Talladega, AL	Non-HVL	PL	▬	Pipe	30"	Resting rock » Dent crack (hairline) (Leak)	-	Soil	1	17, 000
	1989-06-30	Talladega, AL	Non-HVL	PL	▬	Pipe	30"	Resting rock » Dent crack (hairline) (Leak)	-	Soil	1	17,000
	1992-11-03	Cobb, GA	Non-HVL	PL	▬	Pipe	16"	Resting rock » Dent crack (pinhole) (Leak)	-	Soil	2	8,000

A.2. Meteorological Natechs

High wind

	Date	Location	Substance	System Part	Grd	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1999-04-14	Reno, KS	Crude Oil	PMS	▲	Field Pump > Valve	-	High wind > External impact (power pole) » Valve failure	-	Soil	56	4,700
●	2001-04-07	Hancock, IA	HVL	TTF	▲	Injection Piping > Nipple (1/2")	-	Storm > High wind > External impact (board) » Nipple failure	-	Air	176	9,000
●	2001-04-10	McPherson, KS	HVL	PVS	▲	Nipple (1/2")	-	High wind > External impact (valve can whistle) » Nipple failure	-	Air	404	12,000
	2008-11-05	Texas, OK	Crude Oil	AST	▲	Tank > Line Valve	-	High wind > Power outage » Valve malfunction > Tank overflow	-	Soil	25	1,000
	2012-10-13	Lincoln, OK	Crude Oil	TTF	▲	Piping > Fitting (3/4")	-	Storm > High wind > External impact (plywood) » Fitting failure	-	Soil	1	17,000

Heavy rainfall

	Date	Location	Substance	System Part	Grd	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1991-10-30	San Patricio, TX	Crude Oil	AST	▲	Tank > Roof	-	Heavy rain > External load » Sunken roof > Drain	-	Soil	700	211,000
●	1994-09-11	Orange, TX	Non-HVL	AST	▲	Tank > Roof > Manway	-	Heavy rain > External load » Deflected roof > Manway failure > Drain	-	Soil	4,965	22,000
●	1995-01-05	Los Angeles, CA	Crude Oil	TTF	▲	Sump	-	Heavy rain » Sump overflow	-	Sea	5	729,000
●	1996-06-20	Faulkner, AR	Non-HVL	TTF	▲	Slop Tank	-	Heavy rain » Sump overflow (slop tank)	-	Soil	50	< 1,000
●	1998-10-19	Karnes, TX	Crude Oil	AST	▲	Tank > Roof > Side Tank Connection Line	-	Heavy rain > External load » Tilted roof > Piping failure	-	Water	963	3,405,000
●	2001-06-09	Harris, TX	Non-HVL	AST	▲	Tank > Roof	-	Heavy rain > External load » Sunken roof > Drain	-	Soil	2,500	97,000
●	2001-06-09	Harris, TX	Non-HVL	AST	▲	Tank > Roof	-	Heavy rain > External load » Sunken roof > Drain	-	Soil	250	270,000
●	2001-06-10	Harris, TX	Non-HVL	PMS	▲	Slop Tank	-	Heavy rain » Sump overflow (slop tank)	-	Soil	69	8,000
●	2003-09-12	Jefferson, TX	Crude Oil	AST	▲	Tank > Roof	-	Heavy rain > External load » Sump drain malfunction > Tilted roof > Drain	-	Soil	500	56,000
●	2004-07-04	Chariton, MO	Crude Oil	AST	▲	Tank > Vacuum Breaker > Riser	-	Heavy rain + Human contribution (in-proper design) » Riser malfunction > Release onto roof	-	None	130	14,000
●	2004-07-05	Tulsa, OK	Non-HVL	AST	▲	Tank > Floor	-	Heavy rain » Tank floatation > Tank floor failure	-	Soil	120	557,000
●	2006-10-16	Jefferson, TX	Non-HVL	AST	▲	Tank > Roof	-	Heavy rain + High wind > External load » Sunken roof > Drain	-	Soil	15	1,167,000

	Date	Location	Substance	System Part	Grd	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	2007-08-28	Weld, CO	Crude Oil	PMS	▲	Sump	-	Heavy rain > Areal flooding » Sump overflow	-	Water	3	108,000
●	2009-04-28	Chambers, TX	Non-HVL	AST	▲	Tank > Roof	-	Heavy rain > External load » Sunken roof > Drain	-	Water	25	344,000
●	2010-05-16	Galveston, TX	Crude Oil	AST	▲	Tank > Roof > Leg Reinforcing Pad > Weld	-	Heavy rain > External load » Weld failure > Release onto roof > Drain	-	Soil	13	204,000
●	2010-05-16	Assumption, LA	Crude Oil	AST	▲	Tank > Roof	-	Heavy rain + High wind > External load » Tilted roof > Drain	-	Soil	125	1,972,000
●	2012-07-23	Harris, TX	Non-HVL	AST	▲	Tank > Roof	-	Heavy rain + Human contribution > External load » Sunken roof	-	Soil	16	1,853,000
	1994-07-14	Platte, WY	Crude Oil	PMS	▲	Sump	-	Heavy rain » Sump overflow	-	Soil	20	-
	2003-08-14	Jefferson, TX	Crude Oil	TTF	▲	Sump	-	Heavy rain » Sump overflow	-	Soil	< 1	2,000
	2003-08-30	Ector, TX	Non-HVL	TTF	▲	Sump	-	Heavy rain » Sump overflow	-	Soil	< 1	6,000
	2004-07-17	Guilford, NC	Non-HVL	TTF	▲	Oil Manifold > Sump	-	Heavy rain > Areal flooding » Sump overflow	-	Water	16	19,000
	2004-10-02	Bastrop, TX	Crude Oil	AST	▲	Tank > Roof > Drain Line	-	Heavy rain > Debris impact (blockage) » Drain failure	-	Soil	13	30,000
	2007-08-23	Taylor, TX	Crude Oil	PMS	▲	Sump	-	Heavy rain » Sump overflow	-	Soil	5	17,000
	2008-02-13	Lamar, MS	Non-HVL	AST	▲	Tank > Roof > Drain	-	Heavy rain » Drain failure	-	Soil	7	< 1,000
	2008-08-27	Rowan, NC	Non-HVL	PMS	▲	Sump	-	Heavy rain » Sump overflow	-	Soil	< 1	24,000
	2009-10-09	Gregg, TX	Crude Oil	PMS	▲	Sump	-	Heavy rain > Power outage » Sump overflow	-	Water	2	33,000
	2010-06-14	Payne, OK	Crude Oil	AST	▲	Tank > Roof > Manway > Gasket	-	Heavy rain > External load » Gasket failure > Release onto roof > Drain	-	Soil	1	12,000
	2011-07-17	Plaquemines, LA	Crude Oil	PVS	▲	Scraper Trap > Flange	-	Heavy rain » Flange failure	-	Water	2	31,000
	2012-01-10	Calcasieu, LA	Crude Oil	AST	▲	Tank > Roof	-	Heavy rain > External load » Release onto roof > Drain	-	Soil	< 1	10,000
	2012-02-18	Hill, TX	Crude Oil	PMS	▲	Sump	-	Heavy rain » Sump overflow	-	Soil	2	23,000
	2012-04-16	Nueces, TX	Crude Oil	PMS	▲	Sump	-	Heavy rain + Human contribution » Sump overflow	-	Soil	< 1	9,000
	2012-05-03	Mobile, AL	Crude Oil	AST	▲	Tank > Roof	-	Heavy rain > External load » Release onto roof > Drain	-	Soil	8	12,000
	2012-06-08	St. James, LA	Crude Oil	AST	▲	Tank > Roof	-	Heavy rain > External load » Release onto roof > Drain	-	Soil	10	56,000

Storm

	Date	Location	Substance	System Part	Grd	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1989-07-19	Ward, TX	Crude Oil	AST	▲	Tank > Valve	-	Electrical storm > Power outage » Valve malfunction > Tank overflow	-	Soil	300	-
●	1991-07-27	Midland, TX	HVL	PMS	▲	Pump > Mechanical Seal	-	Electrical storm > Power outage » Seal failure	-	Air	35	-
●	1996-05-10	Wood, OH	Crude Oil	PMS	▲	Pipe > Relief Valve > Nipple (1/2")	-	Electrical storm > Communication outage » Overpressure > Nipple failure	-	Soil	100	140,000
●	1998-06-23	Sheridan, MT	Crude Oil	AST	▲	Tank > Pump	-	Electrical storm > Communication outage » Tank overflow	-	Soil	100	9,000
●	2002-05-08	Sedgwick, KS	HVL	PMS	▲	Pump + Relief valve	-	Electrical storm > Power outage » Overpressure > Relief + Lightning > Ignition by lightning	●	Air	1	< 1,000
●	2008-06-26	Allegheny, PA	Non-HVL	TTF	▲	Relief Tank > Relief Valve	-	Electrical storm > Communication outage » Overpressure > Relief > Tank overflow	-	Soil	20	119,000
	2004-06-11	Baltimore, MD	Non-HVL	PMS	▲	Valve	-	Electrical storm > Power outage » Valve malfunction > Relief > Sump overflow	-	Soil	35	39,000
	2005-02-24	Jefferson, TX	Crude Oil	AST	▲	Tank > High Liquid Level Control Transmitter	-	Electrical storm > Power outage » Control switch failure > Tank overflow	-	Soil	5	6,000

Winter storm

	Date	Location	Substance	System Part	Grd	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1997-01-03	Washington, MN	Crude Oil	AST	▲	Tank > Roof	-	Ice/snow > External load (weight) » Sunken roof	-	Soil	475	227,000
●	2010-03-14	Dickinson, IA	Non-HVL	TTF	▲	Block Valve > Pressure Gauge > Nipple	-	Ice/snow > External load (weight) » Nipple failure (Leak)	-	Water	115	537,000
	2011-04-13	Ransom, ND	HVL	PVS	▲	Valve > Blow Down Piping > Fitting	-	Ice/snow > External load (weight) » Fitting failure (Leak)	-	Air	< 1	3,000

Tornado

	Date	Location	Substance	System Part	Grd	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1991-04-29	Rusk, TX	Crude Oil	AST	▲	Tank > Bottom	-	Tornado > High wind > Nearby hit » Tank bottom failure (hole)	-	Soil	215	31,000
●	2009-05-13	Knox, MO	HVL	PMS	▲	Fuel Line > Nipple (1")	-	Tornado > High wind > Direct hit > External impact (light pole) » Nipple failure (Leak)	-	Air	33	7,000

Tropical cyclone

	Date	Location	Substance	System Part	Grd.	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	2004-09-16	Plaquemines, LA	Crude Oil	AST	▲	Tank	-	Hurricane Ivan > Direct hit » Tank failure	-	Sea	3,148	17,652,000
●	2005-08-29	Lafourche, LA	Crude Oil	TTF	▲	Discharge Piping > Nipple (3/4", Threaded)	-	Hurricane Katrina > Storm surge > External impact (floated water tank) » Nipple failure	-	Water	1,276	4,065,000
●	2005-08-30	Plaquemines, LA	Crude Oil	AST	▲	Tank	-	Hurricane Katrina > High wind > Direct hit » Tank failure (floor + roof)	-	Water	23,614	175,395,000
●	2005-08-30	Plaquemines, LA	Crude Oil	TTF	▲	Unknown	-	Hurricane Katrina » Unknown	-	Soil	50	983,000
●	2005-09-02	Plaquemines, LA	Crude Oil	Pipeline	▲	Pipe	20"	Hurricane Katrina > Storm surge > Washout (leeve) » Pipe failure (Rupture)	-	Water	3,245	17,785,000
●	2005-09-02	Plaquemines, LA	Crude Oil	AST	▲	Tank > Bottom	-	Hurricane Katrina > Direct hit » Tank bottom failure	-	Water	25,435	21,954,000
	2005-08-30	Covington, MS	Non-HVL	TTF	▲	Slop Tank	-	Hurricane Katrina » Sump overflow (slop tank)	-	Soil	4	2,000
	2005-08-30	Plaquemines, LA	Crude Oil	PMS	▲	Unknown	-	Hurricane Katrina > High wind » Unknown	-	Sea	2	< 1,000
	2005-09-01	Plaquemines, LA	Crude Oil	TTF	▲	Fitting (Bolted)	-	Hurricane Katrina > High wind » Fitting failure	-	Sea	2	29,000
	2005-09-13	Plaquemines, LA	Crude Oil	AST	▲	Tank	-	Hurricane Katrina » Small spill	-	Water	2	4,000
	2005-09-25	Jefferson, TX	HVL	PMS	▲	Metering Setting	-	Hurricane Katrina > High wind > External impact (pole) » Component failure	-	Air	4	< 1,000
	2005-09-25	Jefferson, TX	Crude Oil	TTF	▲	Piping > Nipple (3/4", Welded)	-	Hurricane Katrina > High wind > External impact (debris) » Nipple failure	-	Soil	15	64,000
	2005-09-26	Galveston, TX	Crude Oil	TTF	▲	Unknown	-	Hurricane Katrina » Large spill	-	Unknown	5	47,000
	2007-08-17	Harris, TX	Non-HVL	TTF	-	Unknown	-	Tropical Storm Erin? » Small spill	-	Unknown	< 1	< 1,000
	2008-09-04	East Feliciana, LA	Non-HVL	AST	▲	Tank > Roof > Drain System > Fitting	-	Hurricane Gustav » Fitting failure	-	Soil	7	17,000
	2008-09-14	Lafourche, LA	Crude Oil	PMS	▲	Sump	-	Hurricane Ike > Areal flood » Sump overflow	-	Water	2	54,000
	2008-09-19	Galveston, TX	Crude Oil	PVS	▲	Nipple (2", Welded)	24"	Hurricane Ike > Storm surge > Washout » Nipple failure	-	Soil	2	22,000
	2012-08-31	Lafourche, LA	Crude Oil	PMS	▲	Sump	-	Hurricane Isaac > Storm surge + Rain » Sump overflow	-	Soil	1	1,000

Lightning

	Date	Location	Substance	System Part	Grd.	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1986-04-13	Marshall, KS	Crude Oil	PMS	▲	Control System + Pump	-	Lightning > Direct hit » Control system failure > Overpressure > Seal failure (Leak)	●	None	-	79,000
●	1986-06-10	Creek, OK	Crude Oil	AST	▲	Tank	-	Lightning > Direct hit » Tank fire	●	None	-	13,000
●	1986-06-14	Payne, OK	Crude Oil	AST	▲	Tank	-	Lightning > Direct hit » Tank fire	●	None	5,577	740,000
●	1986-09-10	Garvin, OK	Crude Oil	AST	▲	Tank	-	Lightning > Direct hit » Tank fire	●	Soil	365	129,000
●	1987-03-25	Ector, TX	Crude Oil	AST	▲	Tank	-	Lightning > Direct hit » Tank fire	●	None	50	164,000
●	1988-07-29	Cobb, GA	Non-HVL	AST	▲	Tank	-	Lightning > Direct hit » Tank fire	●	None	-	44,000
●	1989-09-04	Garfield, OK	HVL	Pipeline	▬	Pipe	4"	Lightning > Direct hit + Corrosion hole » Ignition by lightning (Leak)	●	Air	2	2,000
●	1991-04-04	Harris, TX	Non-HVL	AST	▲	Tank	-	Lightning > Nearby hit » Tank fire	●	None	-	266,000
●	1991-06-14	Kingfisher, OK	Crude Oil	PMS	▲	Control Panel + Discharge Pump	-	Lightning > Direct hit » Control system failure > Pump malfunction > Overflow	-	Soil	5,290	17,000
●	1991-08-28	Nueces, TX	Crude Oil	AST	▲	Tank	-	Lightning > Direct hit » Tank fire	●	None	30	41,000
●	1993-04-13	Gwinnett, GA	Non-HVL	Pipeline	▬	Pipe	40"	Lightning > Direct hit » Hole (electrical arc) (Leak)	-	Water	30	537,000
●	1993-05-20	Gonzales, TX	Non-HVL	Pipeline	▬	Pipe	8"	Lightning > Direct hit » Coil failure > Valve malfunction > Overpressure > Pipe failure (Rupture)	-	Soil	813	97,000
●	1994-07-13	Midland, TX	Crude Oil	AST	▲	Tank	-	Lightning > Direct hit » Tank fire	●	None	-	292,000
●	1994-07-13	Midland, TX	Crude Oil	AST	▲	Tank	-	Lightning > Direct hit » Tank fire	●	None	-	1,460,000
●	1994-09-08	Carson, TX	HVL	Pipeline	▬	Pipe	6"	Lightning > Direct hit » Hole (electrical arc) (Leak)	●	Air	220	6,000
●	1994-10-08	San Patricio, TX	Crude Oil	Pipeline	▬	Pipe	10"	Lightning > Direct hit » Valve malfunction > Overpressure > Pipe failure (Rupture)	-	Sea	2,151	65,686,000
●	1995-06-11	Navarro, TX	Crude Oil	AST	▲	Tank	-	Lightning > Direct hit » Tank fire	●	None	-	71,000
●	1995-11-01	Harris, TX	Non-HVL	AST	▲	Tank	-	Lightning > Direct hit » Tank fire	●	None	-	608,000
●	1995-11-02	Baldwin, AL	HVL	Pipeline	▬	Pipe	6"	Lightning? > Nearby hit » Ignition by lightning (Leak)	●	Air	< 1	23,000
●	1996-06-27	Winkler, TX	Crude Oil	AST	▲	Tank	-	Lightning > Direct hit » Tank fire	●	Soil	100	302,000
●	1996-08-04	Loving, TX	CO2	PMS	▲	Piping > Nipple (1", Welded)	-	Lightning > Direct hit » Nipple failure	-	Air	404	4,000
●	1998-02-10	Hardin, TX	Crude Oil	AST	▲	Tank	-	Electrical storm > Lightning > Direct hit » Tank fire	●	None	-	22,000
●	1998-07-09	Sedgwick, KS	HVL	AST	▲	Tank > Relief Valve	-	Lightning > Direct hit » Valve failure > Tank fire	●	Air	2	20,000
●	1998-08-14	Navarro, TX	Crude Oil	AST	▲	Tank	-	Thunderstorm > Lightning > Direct hit » Tank fire	●	None	-	68,000

	Date	Location	Substance	System Part	Grd.	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1999-06-27	Osceola, FL	Non-HVL	PVS	▲	Pressure Gauge Line (3/8")	-	Lightning > Direct hit » Hole (electrical arc) (Leak)	●	None	-	60,000
●	2000-07-23	Austin, TX	Crude Oil	AST	▲	Tank	-	Lightning > Direct hit » Tank fire	●	None	-	132,000
●	2002-06-01	Union, LA	HVL	Pipeline	▬	Pipe	4"	Lightning > Direct hit » Hole (electrical arc) (Leak)	-	Air	43	73,000
●	2002-07-19	Winkler, TX	Crude Oil	AST	▲	Tank > Roof	-	Lightning > Direct hit » Tank fire	●	None	-	44,000
●	2003-09-26	St. Clair, IL	HVL	PMS	▲	Pump Manifold > Pressure Transmitter	-	Lightning > Ignition by lightning » Engulfing fire > Piping failure	●	Air	200	1,124,000
●	2003-09-26	St. Clair, IL	HVL	PMS	▲	Pump Manifold > Pressure Transmitter	-	Lightning > Ignition by lightning » Engulfing fire > Piping failure	●	Air	1,889	274,000
●	2004-05-18	St. James, LA	HVL	PMS	▲	Valve	-	Lightning > Nearby hit » Ignition by lightning	●	Air	-	6,000
●	2004-06-25	Susquehanna, PA	Non-HVL	PMS	▲	Mainline Valve Pit Cover > Pressure Transmitter Sense Line (1/4")	-	Lightning > Direct hit » Hole (electrical arc) (Leak)	●	Soil	< 1	93,000
●	2004-06-26	Onondaga, NY	Non-HVL	Pipeline	▬	Pipe	10"	Lightning > Direct hit » Hole (electrical arc) (Leak)	-	Soil	110	363,000
●	2004-09-16	Payne, OK	Crude Oil	AST	▲	Tank	-	Lightning > Direct hit » Tank fire	●	None	-	2,820,000
●	2005-03-30	Marion, IL	Crude Oil	AST	▲	Tank	-	Lightning > Direct hit » Tank fire	●	None	-	1,639,000
●	2005-08-03	Orange, TX	Non-HVL	PMS	▲	Main Line > Nipple (1", Threaded)	-	Lightning > Direct hit » Nipple failure	●	None	-	1,000
●	2005-08-08	Orange, TX	HVL	PMS	▲	Valve	-	Lightning > Nearby hit » Valve failure	●	Air	< 1	1,000
●	2005-11-06	Seneca, OH	Non-HVL	PMS	▲	Instrument Tubing	-	Lightning > Direct hit » Hole (electrical arc) (Leak)	●	Soil	2	9,000
●	2006-05-16	Escambia, AL	HVL	Pipeline	▬	Pipe	6"	Lightning > Direct hit » Hole (electrical arc) (1/4") (Leak)	●	Air	400	80,000
●	2006-06-12	Tulsa, OK	Non-HVL	AST	▲	Tank	-	Lightning > Direct hit » Tank fire	●	None	-	6,654,000
●	2006-07-11	Muscogee, GA	HVL	PVS	▲	Tubing Line (3/8")	-	Lightning > Direct hit » Hole (electrical arc) (Leak)	●	Air	< 1	11,000
●	2006-08-05	East Baton Rouge, LA	Non-HVL	AST	▲	Tank > Roof Seal	-	Lightning > Direct hit » Tank fire	●	None	-	36,000
●	2007-01-02	Mobile, AL	HVL	Pipeline	▬	Pipe	6"	Lightning > Direct hit » Hole (electrical arc) (1/8") (Leak)	-	Air	20	57,000
●	2007-01-31	East Baton Rouge, LA	Non-HVL	Pipeline	▬	Pipe	24"	Lightning > Direct hit » Hole (electrical arc) (Leak)	-	Soil	20	771,000
●	2007-10-26	Henrico, VA	Non-HVL	TTF	▲	Instrument Tubing (3/8")	-	Lightning > Direct hit » Hole (electrical arc) (Leak)	●	Soil	< 1	1,000
●	2007-11-05	Hancock, OH	Non-HVL	PMS	▲	Valve Pit > Pressure Transmitter > Sense Line (3/8")	-	Lightning > Direct hit » Hole (electrical arc) (Leak)	●	Soil	< 1	8,000
●	2008-06-03	Wyandotte, KS	Non-HVL	AST	▲	Tank	-	Lightning > Direct hit » Tank fire	●	None	9	10,501,000

	Date	Location	Substance	System Part	Grd.	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	2008-12-29	Limestone, AL	Non-HVL	Pipeline	▬	Pipe	8"	Lightning > Direct hit » Hole (electrical arc) (Leak)	-	Soil	221	1,682,000
●	2009-04-24	Wood, OH	HVL	Pipeline	▬	Pipe	12"	Lightning > Direct hit » Hole (electrical arc) (1/4") (Leak)	-	Air	173	2,527,000
●	2009-07-23	Galveston, TX	Crude Oil	AST	▲	Tank > Roof Seal	-	Lightning > Direct hit » Tank fire	●	None	1	901,000
●	2010-06-12	Salt Lake, UT	Crude Oil	Pipeline	▬	Pipe	10"	Lightning > Direct hit » Hole (electrical arc) (1/2") (Leak)	-	Water	800	33,820,000
●	2011-02-02	Delaware, PA	Non-HVL	PMS	▲	Piping > Dielectric Fitting (3/8")	-	Lightning > Nearby hit » Fitting failure (Leak)	●	Soil	< 1	3,000
●	2012-07-21	Jefferson, TX	HVL	PVS	▲	Pipe	10"	Lightning > Nearby hit > External impact (power line) » Fire impingement (Rupture)	●	Air	3,117	1,183,000
	1989-06-06	Seminole, OK	Crude Oil	Pipeline	▬	Pipe	10"	Thunderstorm > Lightning » Control system malfunction > Overpressure > Pipe failure (Rupture)	-	Water	30	67,000
	1991-03-02	Vermilion, LA	HVL	Pipeline	▬	Pipe	6"	Lightning > Nearby hit > External impact (power line) » Hole (electrical arc) (Leak)	-	Air	2	94,000
	2002-07-10	York, NE	Non-HVL	Pipeline	▬	Pipe	8"	Lightning > Direct hit » Hole (electrical arc) (Leak)	-	Soil	5	46,000
	2003-09-26	St. James, LA	Crude Oil	TTF	▲	Sump Pump > Motor	-	Lightning + Heavy rain » Control system malfunction > Sump overflow	-	Soil	6	9,000
	2008-09-05	Claiborne, LA	Crude Oil	PMS	▲	Sump Motor > Switch	-	Lightning? » Control system failure > Sump overflow	-	Soil	12	16,000
	2010-08-02	El Paso, CO	Non-HVL	TTF	▲	Sump > Relief Valve	-	Lightning > Power outage » Valve malfunction > Relief > Sump overflow	-	Soil	< 1	< 1,000

A.3. Hydrological Natechs

Flood

	Date	Location	Substance	System Part	Grd.	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1987-05-30	Cotton, OK	Crude Oil	Pipeline	—	Girth Weld	24"	Riverine flooding > Washout » Weld failure (Rupture)	-	Water	19,150	630,000
●	1987-05-30	Love, OK	Crude Oil	Pipeline	—	Pipe	8"	Riverine flooding > Washout » Pipe failure (Rupture)	-	Water	1,500	18,000
●	1988-01-02	Caddo, LA	Crude Oil	Pipeline	—	Pipe	8"	Riverine flooding » Unknown	-	Water	355	10,000
●	1989-06-07	Oklahoma, OK	Non-HVL	Pipeline	—	Girth Weld	8"	Riverine flooding > Washout > External loading + Debris impact? » Weld failure (Rupture)	-	Water	2,653	106,000
●	1989-06-13	Carson, TX	HVL	Pipeline	—	Pipe	6"	Riverine flooding > Debris impact? » Pipe failure (Rupture)	-	Water	10,495	175,000
●	1991-06-07	Knox, TX	Crude Oil	Pipeline	—	Girth Weld	10"	Riverine flooding > Washout > External loading + Debris impact » Weld failure (Rupture)	-	Water	6,235	2,235,000
●	1993-04-01	Sioux, IA	Non-HVL	Pipeline	—	Girth Weld	6"	Riverine flooding > Washout » Weld failure (Rupture)	-	Water	390	16,000
●	1993-07-03	Sioux, IA	HVL	Pipeline	—	Pipe	6"	Riverine flooding > Debris impact (tree) » Pipe failure (Rupture)	-	Water	227	60,000
●	1993-07-26	Lancaster, NE	HVL	Pipeline	—	Pipe	6"	Riverine flooding > Bed and bank erosion > Debris impact » Pipe failure (Rupture)	-	Water	2,203	227,000
●	1994-10-19	Harris, TX	HVL	Pipeline	—	Pipe	8"	Riverine flooding > Washout » Pipe failure (Rupture)	-	Water	492	890,000
●	1994-10-20	Harris, TX	Non-HVL	Pipeline	—	Pipe	40"	Riverine flooding > Washout (new bed) » Pipe failure (Rupture)	●	Water	20,000	14,597,000
●	1994-10-20	Harris, TX	Non-HVL	Pipeline	—	Pipe	36"	Riverine flooding > Washout (new bed) » Pipe failure (Rupture)	●	Water	10,000	-
●	1994-10-21	Harris, TX	Crude Oil	Pipeline	—	Pipe	20"	Riverine flooding > Washout (new bed) » Pipe failure (Rupture)	●	Water	5,350	6,552,000
●	1994-12-20	Red River, LA	Non-HVL	Pipeline	—	Pipe	20"	Riverine flooding > Washout » Pipe failure (Rupture)	-	Water	3,181	1,500,000
●	1995-03-11	Fresno, CA	Crude Oil	Pipeline	—	Girth Weld	18"	Riverine flooding > Washout > Debris impact » Weld failure (Rupture)	-	Water	4,000	14,296,000
●	1995-05-21	Madison, IL	HVL	Pipeline	—	Pipe	10"	Riverine flooding > Washout? » Pipe failure (Rupture)	-	Water	72	-
●	1995-06-01	Butler, KS	Crude Oil	Pipeline	▲	Pipe	6"	Riverine flooding > Debris impact (tree) » Pipe failure (Rupture)	-	Water	210	12,000
●	1995-06-06	Cleveland, OK	HVL	Pipeline	—	Pipe	8"	Riverine flooding » Pipe failure (Rupture)	-	Water	1,555	572,000
●	1995-06-07	Kay, OK	Crude Oil	Pipeline	—	Girth Weld	8"	Riverine flooding > Washout > External loading » Weld failure (Rupture)	-	Water	2,526	943,000
●	1997-04-28	Cotton, OK	Crude Oil	Pipeline	—	Pipe	12"	Riverine flooding > Washout > Debris impact » Pipe failure (Rupture)	-	Water	500	14,000
●	1998-10-07	Tulsa, OK	HVL	Pipeline	—	Pipe	10"	Riverine flooding > Washout > Debris impact » Pipe failure (Rupture)	-	Water	1,500	272,000
●	1998-10-18	Colorado, TX	Crude Oil	Pipeline	—	Pipe	8"	Riverine flooding > Washout » Pipe failure (Rupture)	-	Water	100	1,022,000

	Date	Location	Substance	System Part	Grd.	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	2011-07-01	Yellowstone, MT	Crude Oil	Pipeline	▬	Girth Weld	12"	Riverine flooding > Washout > External loading » Weld failure (Rupture)	-	Water	1,509	139,718,000
●	2011-07-15	Burt, NE	HVL	Pipeline	▬	Pipe	6"	Riverine flooding > Washout » Pipe failure (Rupture)	-	Water	100	990,000
●	2011-08-13	Monona, IA	Non-HVL	Pipeline	▬	Girth Weld	8"	Riverine flooding > Washout > External loading » Weld failure (Rupture)	-	Water	675	7,937,000

Stream erosion

	Date	Location	Substance	System Part	Grd.	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1986-09-07	Cooke, TX	Crude Oil	Pipeline	▲	Girth Weld	8"	Scouring > External impact (tree) » Weld failure (Rupture)	-	Water	3,000	18,000
●	1986-10-22	Miami, KS	Non-HVL	Pipeline	▬	Girth Weld	8"	Scouring > Excess stress » Weld failure (Rupture)	-	Water	1,901	18,000
●	1990-03-30	Hutchinson, TX	Non-HVL	Pipeline	▲	Pipe	8"	Dry/wet bed scouring » Corrosion > Pipe failure (Rupture)	-	Water	1,650	89,000
●	1992-07-24	Harris, TX	Non-HVL	Pipeline	▬	Pipe	10"	Washout » Pipe failure (Rupture)	-	Water	1,268	18,000
●	2007-06-14	St. Mary, LA	HVL	Pipeline	▬	Pipe	8"	Scouring > External impact (tree) » Hole (Leak)	-	Water	97	76,000
●	2009-12-23	Plaquemines, LA	Crude Oil	Pipeline	▬	Pipe	16"	Scouring » Unknown (Leak)	-	Water	5	4,673,000

A.4. Climatic Natechs

Hot weather

	Date	Location	Substance	System Part	Grd	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1987-04-13	Garvin, OK	Crude Oil	PMS	▲	Valve	-	Sun pressure » Valve failure	-	Soil	130	4,000
●	2009-03-20	Kern, CA	Crude Oil	PMS	▲	Valve	-	Thermal stress » Valve failure	-	Soil	166	88,000
●	2011-04-03	Harrison, TX	Crude Oil	PMS	▲	Booster Pump > Strainer	-	Sun pressure » Strainer failure	-	Soil	115	10,000
	2010-07-17	Middlesex, NJ	Non-HVL	AST	▲	Thermal Relief Line > Nipple (1")	-	Thermal expansion/contraction > Thermal stress » Nipple failure	-	Soil	7	29,000

Cold weather

	Date	Location	Substance	System Part	Grd	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1986-11-13	Cotton, OK	Crude Oil	PL	▬	Collar	8"	Temperature variation » Collar failure (Leak)	-	Soil	400	9,000
●	1988-01-09	Pontotoc, OK	Non-HVL	AST	▲	Tank > Drain Valve > Bull Plug (4")	-	Low temperature » Component failure	-	Soil	280	< 1,000
●	1989-12-24	Gregg, TX	Crude Oil	PL	▬	Girth Weld	6"	Low temperature » Pipe contraction > Weld failure (Rupture)	-	Water	850	5,000
●	1989-12-26	Haskell, TX	Crude Oil	PMS	▲	Booster Pump > Flange > Gasket	-	Low temperature » Gasket failure	-	Soil	110	< 1,000
●	1990-12-26	Harris, TX	Crude Oil	PL	▬	Pipe	2"	Low temperature > Thermal stress » Pipe failure (Leak)	-	Water	340	324,000
●	1994-02-16	Will, IL	Crude Oil	AST	▲	Tank > Roof > Drain	-	Low temperature » Drain failure	-	Soil	200	80,000
●	1996-02-08	Greene, MO	HVL	PL	▬	Girth Weld	10"	Temperature variation » Weld failure (Rupture)	-	Air	3,000	84,000
●	1996-12-21	Jack, TX	Crude Oil	AST	▲	Tank > Valve (6") > Fitting (Bolted)	-	Low temperature » Fitting failure	-	Soil	1,413	70,000
●	2009-04-14	Lucas, OH	Non-HVL	PL	▬	Pipe	6"	Temperature variation » Pipe expansion > Pipe failure (Rupture)	-	Soil	320	42,000
●	2010-01-11	Calcasieu, LA	HVL	PL	▬	Pipe	6"	Low temperature > Thermal stress » Pipe failure (Leak)	-	Air	2,237	174,000
	1989-12-24	Minnehaha, SD	Non-HVL	AST	▲	Tank > Tank Line > Anchor Support > Expansion Joint	-	Temperature variation > Excessive pressure » Joint failure	-	Soil	6	42,000
	1989-12-25	Minnehaha, SD	Non-HVL	AST	▲	Tank > Tank Line > Anchor Support > Expansion Joint	-	Temperature variation > Excessive pressure » Joint failure	-	Soil	1	42,000
	2011-01-15	Union, NJ	Non-HVL	AST	▲	Tank > Booster Pump > Seal	-	Low temperature » Seal failure (Leak)	-	Soil	< 1	37,000

Freeze

	Date	Location	Substance	System Part	Grd.	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1988-01-27	Wyandotte, KS	Crude Oil	AST	▲	Tank > Tank Line > Valve (3")	-	Ice expansion » Valve failure	-	Soil	1,045	2,000
●	1989-06-20	Howard, TX	Crude Oil	Pipeline	▲	Joint	-	Hydro-testing > Ice expansion » Joint failure (Leak)	-	Water	300	84,000
●	1989-12-11	Douglas, NE	Non-HVL	AST	▲	Tank > Valve	-	Hydro-testing > Ice expansion » Valve failure	-	Soil	110	13,000
●	1991-03-05	Will, IL	Crude Oil	AST	▲	Tank > Roof > Drain Valve	-	Ice expansion » Valve failure	-	Soil	100	4,000
●	1992-02-06	Otoe, NE	Non-HVL	AST	▲	Tank > Water Draw Line > Nipple	-	Ice expansion » Nipple failure	-	Soil	2,899	-
●	1992-11-28	Adams, CO	Non-HVL	AST	▲	Tank > Pressure Relief Line (1")	-	Ice expansion » Piping failure	-	Soil	170	< 1,000
●	1992-12-26	Laramie, WY	Non-HVL	AST	▲	Tank > Valve	-	Ice expansion » Valve failure	-	Soil	185	< 1,000
●	1993-04-09	Pennington, SD	Non-HVL	TTF	▲	Tank > Roof > Drain Hose	-	Freeze? » Piping failure	-	Soil	300	8,000
●	1993-12-19	Adams, CO	Non-HVL	AST	▲	Tank > Discharge Line > Flange > Gasket	-	Ice expansion » Gasket failure	-	Soil	256	-
●	1993-12-28	Kenai Peninsula, AK	Crude Oil	AST	▲	Tank > Nipple (1/2")	-	Falling ice/snow » Nipple failure	-	Soil	380	22,000
●	1994-04-01	Douglas, WI	Crude Oil	TTF	▲	Booster Pump > Piping > Nipple (1/2", Welded)	-	Falling ice/snow » Nipple failure	-	Soil	140	36,000
●	1995-12-08	Fallon, MT	Crude Oil	AST	▲	Tank > Gauge Valve	-	Freeze » Gauge failure > Control system failure > Tank overflow	-	Soil	366	3,000
●	1996-01-03	Upton, TX	CO2	PMS	▲	Meter Station > Relief Valve	-	Ice formation » Valve failure	-	Air	95	-
●	1997-01-29	Tulsa, OK	Non-HVL	TTF	▲	Manifold > Valve	-	Ice expansion » Valve failure	-	Soil	108	28,000
●	2000-01-19	Luzerne, PA	Non-HVL	PMS	▲	Valve	-	Ice expansion » Valve failure	-	Water	120	1,318,000
●	2000-02-14	Boise, ID	Non-HVL	TTF	▲	Piping (6") > Blind Flange	-	Ice blockage > Thaw » Flange failure	-	Soil	160	39,000
●	2000-02-26	Johnson, IA	Non-HVL	TTF	▲	Transfer Line > Flange (Bolted)	-	Ice expansion » Flange failure	-	Water	756	527,000
●	2001-01-27	Rio Arriba, NM	Crude Oil	PMS	▲	Instrument Line > Seal Pot Device	-	Ice expansion » Component failure	-	Soil	130	1,000
●	2001-02-06	Lake, IN	Non-HVL	AST	▲	Tank > Water Draw Line > Valve (4") > Gasket	-	Ice expansion » Gasket failure	-	Soil	75	10,000
●	2002-01-02	Des Moines, IA	HVL	PMS	▲	Prover > Relief Device	-	Ice formation » Component malfunction (relief)	●	Air	< 1	6,000
●	2002-02-03	Johnson, IA	Non-HVL	TTF	▲	Breakout Tank Manifold > Relief Line (1") > Fitting	-	Falling ice/snow » Fitting failure	-	Soil	80	9,000
●	2002-03-03	Fremont, WY	Crude Oil	AST	▲	Tank > Circulation Line (4")	-	Ice expansion » Piping failure	-	Soil	60	5,000
●	2003-01-26	Guilford, NC	Non-HVL	PMS	▲	Fuel Manifold > Booster Pump > Drain Line (2")	-	Ice blockage » Piping failure	-	Soil	2,133	667,000
●	2003-02-27	Monroe, MI	Crude Oil	TTF	▲	Prover > Drain Valve (1")	-	Ice expansion » Valve failure	-	Soil	130	316,000
●	2003-03-17	Cook, IL	Non-HVL	AST	▲	Tank > Roof > Drain Valve	-	Freeze » Valve failure	-	Soil	511	31,000
●	2004-01-16	Laramie, WY	Non-HVL	AST	▲	Tank > Roof > Drain Line > Nipple	-	Ice expansion » Nipple failure	-	Soil	250	80,000

	Date	Location	Substance	System Part	Grd.	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	2004-02-07	Knox, IL	Non-HVL	PVS	▲	Valve	-	Ice expansion » Valve failure	-	Soil	5	400,000
●	2005-01-18	Bay, MI	Crude Oil	PMS	▲	Piping (1") > Union	-	Freeze » Union failure (Leak)	-	Soil	100	53,000
●	2005-02-01	Lehigh, PA	Non-HVL	PVS	▲	Scraper Trap > Launcher Barrel > Valve (2")	-	Ice formation » Valve failure	●	Soil	1,145	5,908,000
●	2007-01-29	Rio Blanco, CO	Crude Oil	AST	▲	Tank > Roof > Drain Piping > Flange > Gasket	-	Ice expansion » Gasket failure (Leak)	-	Soil	3,069	78,000
●	2008-01-25	Polk, IA	Non-HVL	PMS	▲	Pump > Flange	-	Ice expansion » Flange failure (Leak)	-	Soil	2	119,000
●	2009-02-18	Cook, IL	Non-HVL	PVS	▲	Valve	-	Ice expansion » Valve failure	-	Soil	3	254,000
●	2010-01-11	Payne, OK	Crude Oil	AST	▲	Tank > Roof > Drain Hose	-	Ice expansion » Piping failure (Leak)	-	Soil	53	40,000
●	2010-01-21	St. Helena, LA	Non-HVL	PMS	▲	Block Valve > Drain Valve (2")	-	Ice expansion » Valve failure (Leak)	-	Soil	7	210,000
●	2010-03-08	Wyandotte, KS	Non-HVL	AST	▲	Tank > Roof > Drain Line > Elbow Joint	-	Ice expansion » Joint failure (Leak)	-	Soil	168	90,000
●	2010-03-31	Charlotte, VA	Non-HVL	PMS	▬	Leak Detection Tubing > Tee Fitting	-	Ice expansion » Fitting failure (Leak)	-	Soil	1	129,000
●	2011-01-13	Canadian, OK	HVL	TTF	▲	Flare System > Scraper Trap > Insulation Gasket	-	Ice expansion » Gasket failure	-	Air	406	27,000
●	2011-02-05	Nueces, TX	Non-HVL	AST	▲	Tank > Water Draw Line > Valve	-	Ice expansion » Valve failure (Leak)	-	Soil	1,000	119,000
●	2012-01-17	Middlesex, NJ	Non-HVL	AST	▲	Tank > Valve > Flange > Gasket	-	Hydro-testing > Ice expansion » Gasket failure (Leak)	-	Soil	75	317,000
●	2012-01-28	Wyandotte, KS	Non-HVL	AST	▲	Tank > Roof > Drain > Flexible Expansion Joint	-	Ice expansion » Joint failure (Leak)	-	Soil	262	182,000
	1988-01-07	Cook, IL	Non-HVL	TTF	▲	Outfall Separator	-	Ice formation » Component failure (outfall separator)	-	Water	2	5,000
	1989-02-11	DeKalb, GA	Crude Oil	PMS	▲	Pump > Case	-	Ice expansion » Component failure (pump case)	-	Water	40	44,000
	1994-01-28	Gloucester, NJ	Non-HVL	AST	▲	Tank > Water Draw Line > Valve	-	Ice expansion » Valve failure	-	Soil	4	13,000
	1994-02-02	Gloucester, NJ	Non-HVL	AST	▲	Tank > Roof > Drain Line	-	Ice expansion » Piping failure	-	Soil	5	40,000
	1994-04-17	Cumberland, VA	Non-HVL	AST	▲	Tank > Roof > Drain Valve	-	Freeze » Valve failure	-	Soil	5	7,000
	1996-02-08	Phillips, AR	Non-HVL	TTF	▲	Sump > Discharge Line (2") > Elbow Joint	-	Ice expansion » Component failure (elbow}	-	Water	2	2,000
	2000-01-22	Grundy, IL	HVL	TTF	▲	Cave Dehydration System > Free Water Knockout Vessel > Bypass Line (6")	-	Ice formation » Component failure (piping)	-	Air	5	79,000
	2002-01-12	Warren, OH	Non-HVL	AST	▲	Tank > Valve > Nipple	-	Freeze » Nipple failure	-	Soil	40	26,000
	2002-03-19	Fremont, WY	Crude Oil	AST	▲	Tank > Piping	-	Freeze » Piping failure	-	Soil	3	< 1,000
	2002-11-11	Spokane, WA	Non-HVL	AST	▲	Tank > Roof > Flexible Drain Hose > Flexible Joint	-	Ice expansion » Joint failure	-	Soil	14	61,000
	2003-01-29	Carroll, MD	Non-HVL	AST	▲	Tank > Vent Valve (1/2")	-	Ice formation » Valve malfunction	-	Soil	5	7,000

Date	Location	Substance	System Part	Grd.	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
2003-02-01	Fairfax, VA	Non-HVL	AST	▲	Tank > Roof > Drain Line	-	Ice expansion » Piping failure	-	Soil	9	53,000
2004-12-24	Yellowstone, MT	Crude Oil	PVS	▲	Valve > Water Drain Valve	-	Ice expansion » Valve failure	-	Unknown	40	71,000
2005-02-02	Maries, MO	Non-HVL	AST	▲	Tank > Drain Line (2") > Water Draw Valve	-	Ice expansion » Valve failure	-	Soil	23	4,000
2007-02-07	Wayne, MI	Non-HVL	TTF	▲	Densitometer > Piping (2") > Union	-	Freeze/thaw » Union failure (loosening)	-	Soil	14	33,000
2007-04-09	Chippewa, WI	Non-HVL	TTF	▲	Breakout Tank Line > Thermal Relief Valve	-	Ice blockage » Valve malfunction	-	Soil	30	84,000
2008-02-25	Lorain, OH	Non-HVL	PMS	▲	Valve (2") > Plug	-	Ice expansion » Valve failure	-	Soil	4	76,000
2008-12-16	Adams, CO	Non-HVL	TTF	▲	Prover > Drain Line (2") > Ball Valve	-	Ice expansion » Valve failure	-	Soil	25	82,000
2010-01-09	Liberty, TX	HVL	PMS	▲	Thermal Relief Valve (1/2") > Vent Tube	-	Ice expansion » Component failure (valve : crack) (Leak)	-	Air	< 1	< 1,000
2010-01-13	Ascension, LA	HVL	BGS	▲	Dehydration Unit > Drain Line > Valve (1.5" Globe)	-	Ice formation > Thaw » Valve malfunction	-	Air	3	< 1,000
2010-01-14	Cattaraugus, NY	Crude Oil	PMS	▲	Valve > Drain Line	-	Ice blockage » Overflow	-	Soil	< 1	79,000
2010-01-18	Gibson, IN	HVL	AST	▲	Tank > Piping > Nipple (1")	-	Freeze/thaw » Nipple failure (Leak)	-	Air	2	1,000
2010-02-09	Hendricks, IN	Non-HVL	TTF	▲	Instrumentation Line > Pressure Gauge	-	Ice expansion » Gauge failure	-	Soil	< 1	6,000
2010-02-16	DuPage, IL	Non-HVL	PVS	▲	Drain Line > Valve > Gasket	-	Ice formation » Gasket failure (Leak)	-	Soil	< 1	32,000
2010-12-07	Cass, ND	Non-HVL	AST	▲	Tank > Water Draw Line > Ball Valve > Retainer	-	Ice expansion » Component failure (water draw line > valve > retainer) (Leak)	-	Soil	1	6,000
2011-01-03	Gray, TX	Crude Oil	PMS	▲	Drain Line > Pump > Outboard Seal	-	Ice formation » Seal failure (Leak)	-	Soil	< 1	3,000
2011-02-02	Harris, TX	Non-HVL	PMS	▲	Sump	-	Ice formation » Valve malfunction > Sump overflow	-	Soil	6	47,000
2011-02-06	Middlesex, NJ	Non-HVL	AST	▲	Tank > Transfer Line > Blind Flange > Gasket	-	Ice expansion » Gasket failure (Leak)	-	Soil	47	69,000
2011-02-22	Cook, IL	Non-HVL	TTF	▲	Prover > Incoming Line > Ball Valve (1")	-	Ice expansion » Valve failure (Leak)	-	Soil	< 1	10,000
2011-04-12	Huntington, IN	Non-HVL	PVS	▬	Valve > Drain Plug	-	Freeze » Drain plug failure (Leak)	-	Soil	< 1	27,000
2012-01-20	Marion, IL	Crude Oil	AST	▲	Tank > Roof > Drain Valve	-	Ice expansion » Valve failure (Leak)	-	Soil	< 1	5,000
2012-02-19	Washington, MN	Non-HVL	PMS	▲	Prover > Ball Valve (2")	-	Ice expansion » Valve failure (Leak)	-	Soil	< 1	11,000
2012-12-10	McPherson, KS	Crude Oil	PMS	▲	Double Block and Bleed Valve > Piping (1")	-	Ice expansion » Piping failure	-	Soil	7	9,000
2012-12-21	Williams, ND	Crude Oil	PMS	▲	Manifold Area > Valve > Plug (1/2")	-	Hydro-testing > Ice formation » Valve failure	-	Soil	< 1	79,000

Drought

	Date	Location	Substance	System Part	Grd.	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
●	1995-12-25	Palo Pinto, TX	Crude Oil	Pipeline	▬	Collar	8"	Drought > Ground shift » Collar failure (Leak)	●	Soil	300	372,000
●	1995-12-30	Palo Pinto, TX	Crude Oil	Pipeline	▬	Collar	8"	Drought > Ground shift » Collar failure (Leak)	-	Soil	100	86,000

A.5. Other Natechs

Unknown natural

Date	Location	Substance	System Part	Grd.	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
1999-04-30	Gloucester, NJ	Non-HVL	PL	—	Fitting (Welded)	16"	Unknown » Weld failure (Leak)	-	Water	7	94,000
2002-04-21	Cameron, TX	HVL	TTF	▲	Pump	-	Unknown » Small spill	-	Air	-	< 1,000
2002-09-08	San Juan, UT	Crude Oil	PMS	-	Unknown	-	Unknown » Small spill	-	Soil	1	< 1,000
2002-10-30	Essex, VT	Crude Oil	PL	-	Pipe	24"	Unknown » Small spill	-	Soil	< 1	19,000
2003-01-21	Sherburne, MN	Crude Oil	PL	-	Unknown	-	Unknown » Small spill	-	Soil	2	59,000
2003-01-27	Shelby, KY	Crude Oil	PL	-	Unknown	-	Unknown » Small spill	-	Soil	2	12,000
2003-03-01	Clearwater, MN	Crude Oil	TTF	▲	Mainline Valve	-	Unknown » Valve failure	-	Soil	1	59,000
2003-03-12	Marion, IN	Non-HVL	PVS	-	Unknown	-	Unknown » Small spill	-	-	2	< 1,000
2003-04-22	Clearwater, MN	Crude Oil	TTF	-	Unknown	-	Unknown » Small spill	-	Soil	1	25,000
2003-11-10	Douglas, WI	Crude Oil	TTF	-	Unknown	-	Unknown » Small spill	-	Soil	< 1	12,000
2003-11-10	Ramsey, MN	Non-HVL	TTF	-	Unknown	-	Unknown » Small spill	-	-	< 1	< 1,000
2004-01-30	Delaware, PA	Non-HVL	TTF	-	Unknown	-	Unknown » Small spill	-	-	< 1	7,000
2004-02-01	Tulsa, OK	Non-HVL	TTF	-	Unknown	-	Unknown » Small spill	-	-	< 1	3,000
2004-03-10	Douglas, WI	Crude Oil	TTF	-	Unknown	-	Unknown » Small spill	-	-	3	30,000
2004-12-06	Galveston, TX	Crude Oil	PMS	-	Unknown	-	Unknown » Small spill	-	-	< 1	10,000
2004-12-26	Butler, KS	Non-HVL	TTF	-	Unknown	-	Unknown » Small spill	-	-	3	32,000
2004-12-29	Tuscola, MI	HVL	UNK	-	Unknown	-	Unknown » Small spill	-	-	1	7,000
2005-02-21	Wayne, MI	Crude Oil	PMS	▲	Manifold Valve (2")	-	Unknown » Valve failure	-	Soil	3	49,000
2005-09-12	Lafourche, LA	Crude Oil	PL	-	Unknown	-	Unknown » Small spill	-	-	< 1	1,000
2005-10-04	St. Clair, IL	Non-HVL	PMS	-	Delivery Meter	-	Unknown » Small spill	-	Soil	< 1	< 1,000
2005-12-12	Franklin, MO	Non-HVL	PL	-	Unknown	-	Unknown » Small spill	-	Soil	< 1	< 1,000
2005-12-22	Cayuga, NY	Non-HVL	PMS	▲	Drain Valve	-	Unknown » Valve failure	-	Soil	1	2,000
2006-01-09	Clearwater, MN	Crude Oil	TTF	-	Unknown	-	Unknown » Small spill	-	Soil	1	28,000
2006-03-09	Wayne, MI	Non-HVL	PMS	-	Unknown	-	Unknown » Small spill	-	-	< 1	2,000
2006-03-21	Tarrant, TX	Crude Oil	PMS	-	Unknown	-	Unknown » Small spill	-	-	< 1	1,000
2006-06-19	Harris, TX	Crude Oil	PMS	-	Unknown	-	Unknown » Small spill	-	-	4	17,000
2006-12-05	Jim Wells, TX	Crude Oil	PL	-	Unknown	-	Unknown » Small spill	-	Soil	2	1,000
2006-12-05	Grundy, IL	HVL	TTF	-	Unknown	-	Unknown » Small spill	-	Air	4	2,000
2007-01-18	Burlington, NJ	Non-HVL	PMS	-	Unknown	-	Unknown » Small spill	-	-	< 1	11,000
2007-02-26	Wayne, MI	Non-HVL	TTF	-	Unknown	-	Unknown » Small spill	-	-	3	2,000
2007-06-28	Los Angeles, CA	Crude Oil	PVS	▲	Valve Box	-	Unknown » Small spill	-	-	3	1,000

Date	Location	Substance	System Part	Grd.	System Item	Dia.	Impact and Damage Modes	Fire	Medium	Spill (BBL)	Cost (USD)
2007-08-25	Jasper, MS	Non-HVL	PMS	-	Unknown	-	Unknown » Small spill	-	-	< 1	< 1,000
2008-03-20	McPherson, KS	Non-HVL	TTF	-	Unknown	-	Unknown » Small spill	-	-	< 1	< 1,000
2008-03-26	Lee, IL	Non-HVL	PMS	-	Unknown	-	Unknown » Small spill	-	-	< 1	5,000
2008-06-16	Tulsa, OK	Non-HVL	TTF	-	Unknown	-	Unknown » Small spill	-	-	2	18,000
2008-09-05	Lafourche, LA	Crude Oil	PL	-	Unknown	-	Unknown » Small spill	-	Sea	2	54,000
2008-09-09	Douglas, NE	Non-HVL	PMS	-	Unknown	-	Unknown » Small spill	-	-	1	9,000
2008-11-23	Gloucester, NJ	Non-HVL	TTF	-	Unknown	-	Unknown » Small spill	-	Soil	< 1	10,000
2009-01-12	Allen, OH	Non-HVL	TTF	-	Unknown	-	Unknown » Small spill	-	-	< 1	3,000
2009-12-13	Natrona, WY	Crude Oil	AST	▲	Tank > Roof > Drain > Valve	-	Unknown » Valve failure	-	Soil	2	10,000
2009-12-21	Wayne, MI	Non-HVL	-	-	Unknown	-	Unknown » Small spill	-	-	< 1	-

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