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Industrial accidents triggered by earthquakes, floods and lightning: lessons learned from a database analysis

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Abstract Natural hazards and disasters can cause major accidents in chemical and process installations. These so-called Natech accidents can result in hazardous-materials releases due to damage to process and storage units, or pipes. In order to understand the dynamics of Natech events, accidents triggered by earthquakes, floods and lightning recorded in industrial accident databases were analysed. This allowed the identification of the most vulnerable equipment types, their modes of failure due to natural-event impact and the final accident scenarios. Moreover, lessons learned for future accident prevention and mitigation were derived. The analysis showed that pipes and storage tanks are the most vulnerable equipment for earthquakes, floods and lightning, calling for more research of equipment behaviour under natural-event loading. The damage modes and states are strongly dependent on the characteristics of the impacting natural event. Toxic dispersion, fires and explosions were observed as a consequence of all three types of analysed natural events. In the case of floods, two additional scenarios were identified. These are water contamination and the formation of toxic and/or flammable vapours upon reaction of the released chemicals with the floodwaters. The overall number of recorded Natech accidents was found to range from 2 to 5% of all reported accidents in the analysed databases.

Keywords Earthquake · Flood · Lightning · Natech accident · Industrial risk · Lessons learned

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1 Introduction

Numerous industrial accidents have resulted in loss of life and injury, damage to the natural and built environment, as well as significant economic losses. Industrial accidents can be triggered by a number of causes, the most common of which are plant-internal technical or system failure, human errors or a combination of both (Rasmussen 1995). Industrial activities may, however, also be subject to accident-initiating factors external to an installation, such as sabotage or natural disasters. A growing body of literature by European and United States researchers highlights the potential for natural disasters to trigger the release of hazardous substances from chemical facilities that process or store these materials (e.g. Krausmann and Cruz 2008; Steinberg and Cruz 2004; Young et al. 2004; Valleé 2004; Lindell and Perry 1997). This kind of technological accident is also referred to as *Natech* accident (Showalter and Myers 1994). It includes natural-disaster-triggered spills and releases from fixed chemical installations, as well as oil and gas spills from pipelines.

Natural hazards and disasters can trigger multiple and simultaneous failures in chemical facilities with often severe off-site consequences as recent examples show. The 2008 Wenchuan earthquake in China with a moment magnitude $M_W = 7.9$ hit a heavily industrialised area, causing widespread damage to production and storage facilities and releasing toxic, flammable and explosive materials which impacted the population and the environment (Krausmann et al. 2010). In one case, a toxic ammonia cloud was reported to have engulfed a village, causing fatalities and injuries. In 2005, Hurricanes Katrina and Rita wreaked havoc on offshore oil and gas production facilities in the Gulf of Mexico, as well as on on-shore processing and storage facilities. With the Gulf region accounting for 30% of the United States' oil supply and 20% of its natural gas, the shutdown of production led to domestic oil and gas shortage as well as to a hike in oil prices (Cruz and Krausmann 2008). The hurricanes and the ensuing storm surge also triggered numerous hazardous-materials releases with oil spills totalling over 30,000 m^3 (Davis 2006).

Natech risk is on the rise due to the predicted increase in the frequency and/or intensity of hydro-meteorological hazards by climate change (Parry et al. 2007) and growing industrial development. Recent surveys by Krausmann (2010) and Krausmann and Baranzini (2009) found that lightning and floods are among the most frequent natural hazards that have triggered chemical accidents in OECD Member Countries and EU Member States. Antonioni et al. (2009) indicate that earthquakes have resulted in the most severe Natech events. However, methodologies to assess Natech risk are scarce, and only recently a framework for the quantitative assessment of this type of risk was proposed (Antonioni et al. 2009). The application of this framework requires equipment vulnerability models that link the severity of the natural hazard to its impact on specific equipment types. Since these models are not easily available, an analysis of Natech accidents triggered by earthquakes, floods and lightning recorded in the major industrial-accident databases was performed to identify the most vulnerable equipment categories, their failure modes and the resulting accident scenarios. This study, which builds upon prior work by the authors (Campedel et al. 2008a; Renni et al. 2010; Cozzani et al. 2010), presents and compares the main results of the accident analysis. It highlights key lessons learned and proposes accompanying recommendations for accident prevention and mitigation for the analysed natural events.

2 Methodology

2.1 Data sources consulted for the accident analysis

Accident case histories were extracted from the main European industrial-accident databases ARIA (2006), FACTS (2006), MARS (2008), MHIDAS (2001) and TAD (2004), as well as from the US National Response Centre's (NRC) database (2008). The analysed databases contain accident data from the open technical literature, government authorities or in-company sources. In some cases, open-literature information was used to supplement the information in the consulted databases or when accidents of interest were not recorded (Gautam and van der Hoek 2003; Reinders and Ham 2003; Campedel 2006). All the above databases were used to retrieve information on chemical accidents triggered by earthquakes, floods and lightning, with the exception of ARIA and FACTS due to the unavailability of the earthquake and lightning data subset, respectively.

2.2 Data selection criteria

For the purpose of this study, we selected only those Natech events that occurred in fixed chemical installations, which house or process hazardous substances in relevant quantities, and in pipelines. These installations, which include e.g. oil refineries, high-capacity storage tank farms, pesticides or pharmaceuticals manufacturing sites etc., have the potential to generate a major accident with possible off-site consequences. The equipment categories of interest were defined on the basis of systematic studies on equipment classification in process plants (Uijt de Haag and Ale 1999; Delvosalle et al. 2006; Tugnoli et al. 2007). This classification is based on substance properties and storage capacity, operating or storage conditions and the severity of potential accident scenarios associated with each equipment category. Therefore, we extracted only those records from the accident databases where the following equipment items were involved:

- Storage: atmospheric or pressurised storage tanks, warehouses;
- Processing: reactors, heat exchangers, columns, separators, others;
- Auxiliary: pipework, pumps and compressors;
- Pipelines (only for floods and earthquakes).

As a result, 79 records for Natech accidents triggered by earthquakes, 272 caused by floods and 721 triggered by lightning were collected from the analysed databases. The extracted data were mainly of categorical nature. In addition, numerical data were considered whenever available. Table 1 gives an overview of the number of retrieved Natech events per natural hazard and database.

Table 1 Number of retrieved Natech accidents per database and natural hazard

Natural hazard	ARIA	FACTS	MARS	MHIDAS	TAD	NRC	Other	Total
Earthquakes	–	1	–	9	11	44	14	79
Floods	72	14	1	13	13	154	5	272
Lightning	45	–	4	79	9	584	–	721

2.3 Data quality

The quality of the information reported in the analysed industrial-accident databases was not homogeneous and often suffered from a lack of detail or accuracy. This is due to the difficulty of finding qualified information sources, especially in situations where accident reporting by the industry or by authorities is not compulsory and has to rely on voluntary record keeping.

The level of detail of the recorded information varied across the reported accidents depending on whether the consequences of the Natech event were major or minor, and on whether sufficiently detailed information was available for reporting. In the analysed case histories, especially the accident description was very general and did not usually provide details on the failure modes that eventually resulted in the loss of containment or in the final damage states. Therefore, it was difficult to reconstruct the dynamics of the accidents and to define what the most probable damage modes were that led to the final accident scenarios. Another problem was the frequent lack of data on the severity of the natural event that triggered the Natech accident. This information is required for the development of equipment vulnerability models which link the natural-event severity, e.g. the water height and speed at the industrial site, to the observed damage states that have resulted in a loss-of-containment scenario. Consequently, in the following the analysis of specific problem areas was limited to the data subsets that presented the required level of detail.

The study also showed that conventional industrial-accident databases are usually not designed to capture all the characteristics of chemical accidents triggered by natural events which necessitate a more sophisticated representation. Therefore, an accident database dedicated to the systematic collection of Natech accidents was set up to assist in the prevention and mitigation of future Natech accidents (European Commission 2010).

3 Results and discussion

The analysis of the industrial accident databases presented in Sect. 2.1 shows that overall between 2 and 5% of the recorded accidents were triggered by natural hazards or disasters (this does not include the NRC database for which the total number of accidents was not available). This could be an underestimation as we observed a reporting bias towards accidents with severe consequences. Accidents are more likely to be reported if they resulted in a strong societal impact and received media attention. Low-consequence accidents could therefore be underreported, in particular in the absence of reporting obligations, when consequences are below a pre-defined threshold (Young et al. 2004).

3.1 Earthquake impact on process and storage equipment

The parameters used to characterise the earthquake severity and its damage potential are peak ground motion parameters (peak ground acceleration (PGA), peak ground velocity, peak ground displacement) and the spectral acceleration (Singh 1995). While PGA alone may not be a sufficient measure for an earthquake's damage potential (Farzad and Anderson 1993), it is commonly used in earthquake-engineering applications due to it being the simplest proxy and because of the easiness of measurement (Campedel et al. 2008b). Most earthquake damage to structures is a result of loading by direct shaking. These shaking forces consist of two horizontal shaking amplitudes and a vertical component which in building codes is generally assumed to be lower than the horizontal

amplitudes. It is interesting to note that this is not necessarily always the case and failure to take this into account in the building design can exacerbate earthquake damage (Paterson et al. 2008). In addition to direct shaking forces, soil-liquefaction effects can result in foundation failures and thereby cause damage to or the collapse of engineered structures.

The database analysis using the 79 retrieved earthquake-triggered accidents showed that pipework and transport pipelines with 65% of equipment involved, and tanks for the atmospheric storage of chemicals with 33% appear to be particularly vulnerable to excitation and damage by the earthquake forces. Interestingly, in many of the analysed Natech accidents, several equipment items of the same type were damaged or destroyed per earthquake event, as well as more than one equipment type. The high vulnerability of atmospheric storage tanks as opposed to pressurised ones is a result of design and construction differences that take into account the different operating conditions. Mannan (2005) indicates that the minimum design pressure for pressurised storage tanks is 103.4 kPa gauge pressure (204.8 kPa absolute pressure). Accordingly, their shell thickness and therefore their resistance to damage are significantly higher than that of atmospheric tanks. Existing vulnerability models reflect this by assigning much lower damage probabilities to pressurised tanks than to atmospheric tanks for the same PGA.

Only 32 accident reports (out of 79) provided information on the type of damage observed. Their analysis indicates that in 27% of the cases only structural equipment damage occurred while in 73% damage with the release of hazardous materials was observed. These results seem to suggest that chemical equipment is much more likely to suffer damage with loss of containment than not. Consequently, accident scenarios with significant severity could result more easily and frequently. These conclusions are, however, subject to uncertainty due to the likely underreporting of low-consequence accidents.

The analysed accident case histories allowed the definition of two equipment damage and failure subcategories without release (minor and moderate) and of three with release (minor, severe, catastrophic). The percentage of accident records for each subcategory is shown in Fig. 1. The observed associated structural damage modes are summarised in Table 2. Salzano et al. (2003) suggest that elephant-foot buckling is the most common tank-shell damage under earthquake loading. It is usually only observed for anchored tanks with a height-to-radius ratio of >0.8. Damage to the tank shell was also found to be caused by sloshing of the liquid stored in tanks. This is a particular problem for full or nearly full tanks (Ballantyne and Crouse 1997). Liquid sloshing is also an important contributing

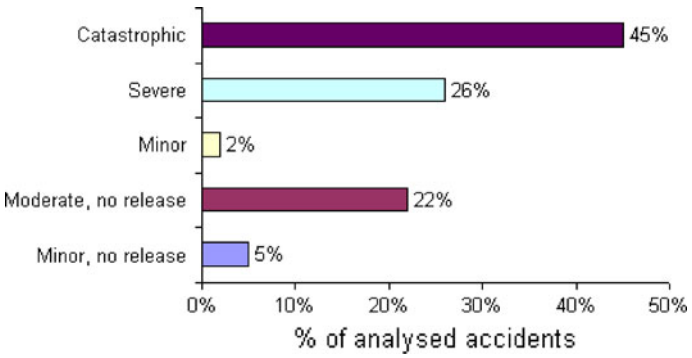


Fig. 1 Percentage distribution of earthquake-triggered accident records per damage and failure subcategory (based on 32 accident records)

Table 2 Structural damage and failure modes observed in the analysed earthquake-, flood- and lightning-triggered Natech accidents

	Earthquakes	Floods	Lightning
Structural damage without release			
Minor	Elephant-foot buckling, deformation of support structures, stretching of bolts, sloshing damage	–	–
Moderate	Detachment of bolts, failure of connections/welds, tank roof-top failure, failure of columns and support structures	–	–
Structural damage with release			
Minor	Partial failure of flanges and connections	Partial failure of flanges and connections, damage due to impact with floating objects	Partial failure of connections, full-bore rupture of small-diameter pipes
Severe	Failure with loss from the tank roof top or shell	Complete failure of connected piping, tank floating, roof failure and/or shell rupture	Full-bore rupture of large diameter connections, shell rupture
Catastrophic	Collapse or overturning of tank	Collapse, implosion, impact of adjacent floating vessels	Collapse of vessel

factor in the collapse of tanks during earthquakes which can lead to the instantaneous release of the complete tank inventory (Ballantyne and Crouse 1997).

The most frequent final scenarios triggered by earthquakes were fires and the release of hazardous materials without ignition (based on the analysis of 48 case histories). In addition, explosions, the dispersion of toxic substances and water contamination were also observed.

In order to understand how frequently the hazardous materials released during earthquakes were ignited, a subset of 29 accident records involving only storage tanks containing flammable substances was analysed in more detail. The results also provided some interesting insights into the destructive potential of the earthquake forces when they hit storage tanks. In fact, in one accident an earthquake damaged 97 storage tanks at a single blow. An ignition probability of 0.76 was calculated by comparing the number of accidents with only release to those with release and ignition. It should be noted that this probability is most likely an upper limit as it is based on reported Natech accidents and generally only accidents with rather severe consequences get reported.

There was not enough information in the accident records to identify the substances most frequently involved in the accidents. However, the high vulnerability to earthquakes of atmospheric storage tanks and transport pipelines, as well as the frequent occurrence of fires suggests that the release of hydrocarbons was common.

Information on the earthquake severity is commonly available. Therefore, for some equipment categories simplified vulnerability models exist for use in the quantitative risk analysis of chemical facilities in earthquake-prone areas (Fabbrocino et al. 2005; Campedel et al. 2008b). Nevertheless, the results of the analysis of accident records can prove useful for the refinement of existing models and for the development of models for different types of equipment.

3.2 Flood impact on process and storage equipment

Floods can be characterised by their return period and their severity which is a function of the water depth, the water speed and the duration of the inundation. For the purpose of assessing the potential damage to chemical facilities, the inundation height and the water speed are the two most important parameters. Floodwaters can impose different loads on industrial buildings and equipment (Yeh et al. 2005) which include the following:

- Hydrostatic loads (both vertical and lateral) which occur when standing or slowly moving water encounters buildings or equipment;
- Hydrodynamic loads which are generated by water moving at moderate to high speed;
- Impact loading which results from collision with floating debris.

These forces can determine the collapse of vessels, the yielding of support structures or the possible failure of flanges and connections at industrial installations. Knowledge of the overall pressure acting on facilities from the above forces and its correlation with equipment failure modes and damage states is a prerequisite for developing simplified vulnerability models.

In the analysis of flood-triggered Natech case histories, accidents caused by river and flash floods were included. The results are, however, equally valid for storm-surge conditions. Only 48 accident records out of 272 provided information on the inundation height and/or water speed. In only 21 records, the water height was quantified (Table 3) while most of the data on the flood severity were of qualitative nature. Not surprisingly, more accidents were reported for moderate to high water levels than for low water depths. There is even less information on the water speed with only 10 records specifying this parameter. All of them indicate conditions of high flow rate (8 due to flash floods) during the accident.

The accident analysis indicated that the most vulnerable equipment categories are storage tanks with 74% of the equipment involved in flood-triggered accidents, followed by transport pipelines and pipework with 17% (Fig. 2). Cylindrical vessels (condensers, separators and boilers) and compressors and pumps were involved in 5 and 4% of accidents, respectively. Similar to earthquake-triggered Natech accidents, the data highlight the particular vulnerability of atmospheric storage tanks which account for at least 75% of all accidents at storage activities. In contrast, only 18% of the analysed accidents involving storage occurred in pressurised tanks and vessels. Due to the lower structural resistance of atmospheric tanks, a specific water depth and hence hydrostatic load are sufficient to collapse the tank shell or induce tank floating. In order to damage pressurised tanks, e.g. by loosening their anchorage saddles, strong hydrodynamic forces generated by a high water speed are required.

In only 55 records (out of 272), information on the accident dynamics resulting in damage to equipment due to flood impact was provided. The analysis results suggest that

Table 3 Number of accident records and percentage distribution as a function of inundation height (based on a subset of 21 records)

Inundation height (m)	Number of accident records (%)
$h < 0.5$	5 (24)
$0.5 \leq h < 1$	5 (24)
$h \geq 1$	11 (52)

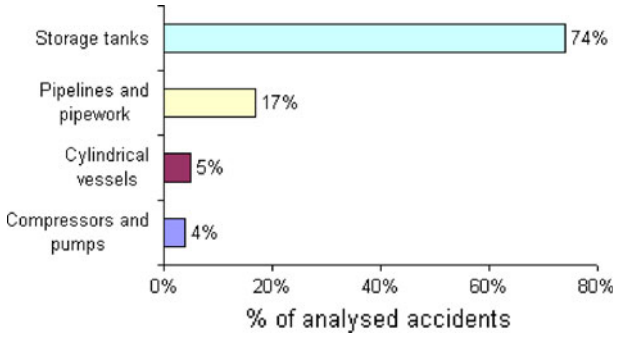


Fig. 2 Equipment types involved in flood-triggered Natech accidents (based on 272 accident records)

the main cause for loss of containment during floods is the failure of connections and valves, pipework detachment, as well as failure of pipelines. This kind of failure was a result of flood-induced equipment displacement which strained or broke connections. This usually led to minor leaks of hazardous substances. The displacement of equipment due to water drag, tank overturning or floating was also frequently observed and has resulted in more severe, continuous releases. Tank collapse due to water drag and/or pressure resulted in several cases in catastrophic loss of containment with instantaneous release of the complete equipment inventory. The types of flood-triggered equipment damage and failure modes and their severity are summarised in Table 2.

Since atmospheric storage tanks were the equipment type most susceptible to flood impact, the hazardous substances found to be most frequently involved in flood-triggered Natech accidents were gasoline, oil and diesel, usually stored in this type of vessel (67% of accidents). This is of particular concern as these substances are extremely flammable and dangerous for the environment. In addition, these tanks may have a high storage capacity (up to 50,000 m^3 in a single unit) and can therefore cause accident scenarios with significant severity should loss of containment occur. A limited number of releases of liquefied petroleum gases and of other hazardous materials from pressurised tanks was also observed.

The analysis of the only 170 accident records (out of 272) that provided information on consequences indicated that water contamination was the most frequent final accident scenario. In some cases, the presence of the floodwaters resulted in the spreading of the released substances over wide areas, possibly contaminating surface and groundwater. Where an unconfined liquid pool formed, soil contamination was a likely result. The impact of floods on chemical installations also resulted in fires, explosions, as well as in the dispersion of toxic vapours or gas. The analysis also showed that in some Natech events triggered by floods, the released hazardous substances violently reacted with the floodwaters, thereby generating toxic or flammable gases. These gaseous reaction products can in turn cause further fires and explosions. It is therefore of paramount importance that the potential occurrence of these secondary reactions be taken into consideration when assessing the risk due to flood-induced accidents (Cozzani et al. 2010).

3.3 Lightning impact on process and storage equipment

Several studies indicate that lightning strikes on equipment in storage and processing activities are the most common cause of accidents triggered by natural hazards (Rasmussen

1995; Chang and Lin 2006). Although lightning protection measures, e.g. the grounding of tanks or the installation of lightning rods, are often implemented, their efficiency in preventing lightning-triggered fires is unclear (Goethals et al. 2008). In fact, there is controversy on the use of tank shunts to safely conduct stray electrical currents as they have been found to potentially generate sparks when struck by lightning (Industrial Fire World 2006). This could ignite flammable vapours if present on tank roofs rather than prevent fires. Equipment can be damaged either by direct lightning strike or by indirect effects such as the build-up of the bound charge and subsequent secondary sparking (American Petroleum Institute 2008). Lightning can also disrupt electrical control and safety systems and thereby cause dangerous process upsets that can result in hazardous-materials releases and fires (US Environmental Protection Agency 1997). At present, there exist no detailed models that quantify the risk of lightning strikes on chemical equipment.

Based on the analysis of 485 accident records (out of 721) that provided the required information, storage tanks were the equipment category most frequently damaged by lightning impact (60% of equipment involved in accidents). In accordance with the results for floods and earthquakes, atmospheric tanks, and in particular tanks with floating roofs, were the tank types most vulnerable to lightning strikes. Out of the 289 accidents involving storage tanks only in 2 cases pressurised storage tanks suffered loss of containment due to lightning. Pipework was directly involved in over 11% of lightning-triggered accidents. Flare stacks, which are elevated vertical stacks or pipes for the combustion of waste gas, and electrical and electronic systems, have also been found to often be affected by lightning (25%). While their failure may not directly lead to a loss of containment, secondary effects such as e.g. collapse, the loss of electricity or water for cooling purposes or computer-equipment failure and software lock-up have caused the release of hazardous substances.

From the analysis of 604 accident case histories (out of 721) that provided this information, three main damage mechanisms that led to a loss of containment were identified. As Fig. 3 shows, in the majority of cases (38%) the lightning strike ignited flammable vapours present near the equipment. The ignition is immediate and does not require a preceding loss of containment due to structural damage by the lighting. In 35% of the accidents, releases were a consequence of the disruption of electrical or electronic systems by the electrical field created by the lightning. These systems – e.g. control valves, process

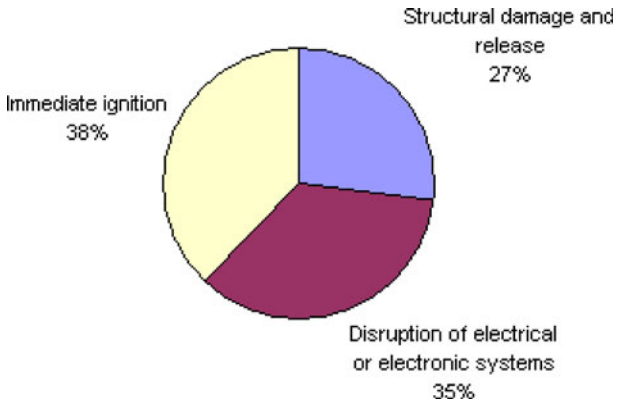


Fig. 3 Damage mechanisms that led to a loss of containment observed in lightning-triggered accidents (based on 604 accident records)

or safety instrumentation, etc. – can be essential for the safety of the equipment, and their failure can therefore indirectly result in a loss of containment. Structural damage due to direct lighting strikes and subsequent releases were observed in 27% of the analysed accidents. In the case of atmospheric storage tanks, the lightning's current intensity may be sufficient to melt the thin tank shell, exposing its often flammable content. Delayed ignition can be the consequence. Table 2 summarises the observed structural damage and failure modes following a lightning strike.

Based on the analysis of 713 accident case histories, oil, diesel and gasoline were the substances most frequently released during lighting-triggered accidents (55%). In 32% of the records, loss of containment of oxides (which are explosive) and natural gas (which is extremely flammable and explosive) occurred. The released quantities were usually significant, and in 38% of a subset of 335 accident records, the release exceeded 1,000 kg.

The majority of lightning-triggered accidents resulted in the release of hazardous materials which did not ignite or explode, as shown in Fig. 4. Dispersion and/or water and soil contamination can follow the release. Fires occurred in over a third of the analysed case histories while a lower number resulted in explosions. Ignition can occur when a flammable vapour cloud or a stratified substance on the ground suffers a direct lightning strike, or due to secondary lightning effects, such as, an electromagnetic or electrostatic pulse, earth currents or the bound charge. Carpenter (2004) indicates that the secondary effects of a direct or nearby lightning strike are the main causes of petroleum-related fires. As in Sect. 3.1, an upper limit of 0.82 for the ignition probability at storage tanks following loss of containment due to lightning was estimated by comparing the number of accidents with only release of flammable substances and those with release of flammable substances followed by ignition and fire. This is slightly higher than the one for earthquakes; however, in contrast to earthquakes, lightning constitutes an ignition source in itself. Similar to floods, in the case of rainstorms that accompany a lightning event some released substances can react with the rainwater and generate toxic and/or flammable gases which pose an additional risk (Cozzani et al. 2010).

3.4 Key lessons learned and recommendations

Based on the conclusions of the accident analysis and other studies related to the investigation of Natech accidents and their dynamics (e.g. Krausmann et al. 2010;

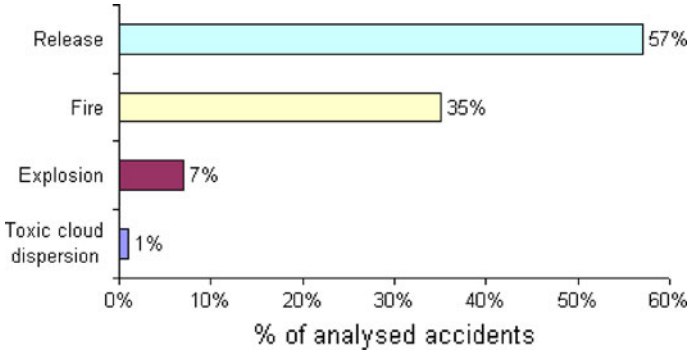


Fig. 4 Percentage distribution of accident scenarios initiated by lightning strikes (based on 721 records)

Cozzani et al. 2010; Cruz et al. 2010; Cruz and Krausmann 2009; Krausmann and Mushtaq 2008), a set of key lessons learned and accompanying recommendations in support of future accident prevention and mitigation were formulated. This includes lessons on the performance of equipment, as well as on organisational issues, such as emergency planning. Examples of key lessons learned and accompanying recommendations for accident prevention and/or mitigation specific for earthquakes, floods and lightning are presented in Table 4.

The accident analysis presented in the previous sections highlighted some commonalities between the impact of earthquakes, floods and lightning on process equipment. The susceptibility of atmospheric storage tanks, and in particular floating-roof tanks, to damage by the three considered natural events is striking. This is of particular concern as these tanks are commonly used for the storage of flammable liquid hydrocarbons and may have a high storage capacity. Therefore, loss of containment can lead to a major accident. Not surprisingly, the hazardous materials most frequently released were oil, diesel fuel and gasoline. Moreover, the ignition probability is high after the release of a flammable substance during an earthquake or a lightning strike. These results indicate the need for a more detailed analysis of the behaviour of atmospheric storage tanks under natural-event loading to identify adequate protection systems and measures.

Experience shows that managing Natech risk is difficult if industrial facilities have not adopted targeted measures or procedures to prevent a Natech accident or to reduce its possible consequences. This is of particular importance in natural-hazard-prone areas that are already heavily industrialised and where land-use-planning restrictions are difficult to impose retroactively. Industrial facilities in natural-hazard zones should therefore identify the possible failures of equipment triggered by a natural event, and its potential consequences. Based on this, measures can be taken to increase the resilience of the facility. Increasing the sturdiness of equipment or adding safety barriers is an example of addressing the problem at the design level. The elaboration of appropriate emergency measures and procedures coupled with the implementation of early-warning systems—where feasible—could allow sufficient lead time for preventive measures to be taken to reduce the exposure or vulnerability of equipment and processes (e.g. shutdown of critical processes and systems).

An additional complication in most Natech accidents is the downing of lifelines by the natural event. Emergency-response plans do not usually consider the loss of utilities during a natural disaster, which renders the mitigation of the accident difficult if not impossible. Plant-internal emergency plans should take this into account and provide e.g. for backup lifelines or specific emergency procedures to cope with the consequences of the Natech accident.

The Natech risk management framework includes purely technical issues for accident prevention and mitigation, but it also comprises human and organisational factors, as well as risk governance outside the organisation. Recent studies showed that legislation, codes and standards for the prevention of chemical accidents do usually not explicitly address Natech risk (Krausmann 2010; Krausmann and Baranzini 2009). These studies also indicated a lack of methodologies and tools for Natech risk assessment, as well as a need for guidance for industry and the national authorities on how to assess Natech risk. Poor Natech risk communication at all levels of government and in industry was also identified. These aspects will be addressed in future work.

Table 4 Key lessons learned and accompanying recommendations for earthquakes, floods and lightning

	Lessons learned	Recommendations
Earthquakes	Floating-roof tanks are prone to fire scenarios during an earthquake. Liquid sloshing can result in bouncing of the metallic roof against the side wall which could create sparks and ignite the tank content if flammable	The risk associated with floating roof tanks in areas where an earthquake hazard exists needs to be re-evaluated
	Liquid sloshing can compromise the structural integrity of tanks which are full or nearly full	Liquid sloshing and the resulting dynamic loading on the tank wall needs to be taken into account in the risk assessment in earthquake-prone areas
	Rigid connections between pipes and equipment are vulnerable to shaking damage and failure which can lead to the release of hazardous materials	Specific connections should be used in earthquake-prone areas
	Safety barriers to prevent an accident or mitigate its consequences, such as e.g. catch basins around tanks or sprinkler systems, may fail under earthquake loading	Critical active and passive safety barriers in the facility need to be designed to withstand the forces of the expected earthquake
	Non-anchored equipment can suffer damage through lateral displacement and/or uplifting	Anchoring or restraining of equipment could effectively avoid displacement and keep the equipment intact
	Earthquakes can trigger multiple releases at a single chemical facility or from several affected hazardous installations simultaneously.	The characteristics of an earthquake impact on a chemical facility, and the possibility of a domino effect*, need to be considered in land-use-planning decisions and when preparing emergency response plans. In particular, on-site emergency planning needs to take into account that off-site response resources may not be available as they may be busy fighting the consequences of the natural disaster. On the other hand, off-site emergency plans should consider the potential earthquake-triggered release of hazardous materials and its possible impact on rescue operations
		The implementation of earthquake early-warning and rapid response systems at facilities would be useful to enable the automatic shutdown of critical systems in the case of an earthquake
	Structural damage to and collapse of warehouses, offices and manufacturing buildings is an important cause of worker death	Seismic building codes based on a realistic assessment of the expected earthquake severity and the resultant loading on structures need to be implemented. Compliance with these codes needs to be monitored
		Seismic design codes should be extended to also cover industrial equipment where not mandatory

Table 4 continued

	Lessons learned	Recommendations
Floods	Equipment can suffer damage or failure due to flotation upon flood impact. Moreover, the displacement of floating tanks can tear pipe connections and lead to hazardous-materials releases	Adequate anchoring with bolts or other types of restraining systems should effectively prevent tanks and other equipment from floating off their foundations for most flood conditions
		The filling of empty tanks with water in preparation for a flood could ensure that they do not suffer buoyancy. This measure necessitates the implementation of safety procedures to avoid contamination, reaction or other damage and, therefore, requires early warning
		Leaving a specified amount of product stored in tanks at all times could keep them from floating off their foundations. However, in the case of tank failure the consequences could be more severe
	Flooding of electrical equipment can lead to short-circuiting and power blackouts which could result in the failure of cooling units, pumps and electrically operated safety systems	Safety–critical systems need to be protected from wave-load damage and water intrusion. This can be achieved by waterproofing and appropriate design of sensitive equipment and systems.
		Safe equipment design (e.g. using interlocks, fail-open or fail-closed valves, etc.) ensuring safe emergency shutdown during loss of on-site power can contribute to reducing the risk of an accident
	The impact of floating debris dragged along with the floodwaters poses a threat to equipment and can lead to the release of hazardous substances	External barriers, such as earthen berms, sheet-pile or concrete walls, can keep flood-driven debris from washing into a facility
	Some hazardous materials released due to flood impact can react with the floodwaters to generate toxic or flammable vapours, which pose a secondary threat	Possible violent reactions with the floodwaters need to be considered in the industrial risk assessment in flood-prone areas
	Waste oil in the plant drainage system can be lifted by the floodwaters and cause fires and/or explosions upon contact with an ignition source (e.g. hot equipment or lightning)	The drainage systems for waste flammable substances and surface run-off water should be segregated
	Floods usually affect a wide swath of land and can carry released substances over significant distances. Therefore, the risk of a domino effect in a densely industrialised area is elevated	A flood hazard management plan needs to be drawn up at plant and community level. This plan needs to incorporate the emergency evacuation of workers and residents in view of the inundation of the facility and the hazardous-materials releases possibly triggered by it. Particular attention needs to be given to potential impact of the release of toxic or flammable substances on the rescue operations
		If the siting in a flood-prone area of a new hazardous facility cannot be avoided, then the plant layout should attempt to place safety–critical plant components or equipment containing hazardous materials outside the estimated inundation zone

Table 4 continued

	Lessons learned	Recommendations
Lightning	Lightning is a frequent source of fires in tanks containing flammable substances. The rim seal of atmospheric floating-roof tanks is the most likely point of ignition during a lightning strike	The rim seal should be regularly checked and maintained in good condition to limit the escape of flammable vapours, which can be ignited by lightning
	Lightning can lead to partial or total on-site power outage and power dips which can result in process upsets and loss of containment	As standard procedure, dangerous conditions resulting from loss of power should be identified to determine which processes should receive power from internal backup systems. Emergency shutdown of highly hazardous processes and blow-down of pressurised equipment should be effected to put units into safe mode
	Lightning can affect electronic systems or electrically operated safety systems whose damage or failure can lead to dangerous conditions during start-up of the installation after a thunderstorm	Safety–critical systems need to be protected from the impact of a lightning strike. Moreover, the installation needs to be carefully monitored during the start-up phase to detect possible malfunctions threatening the safety of the plant
	Lightning protection measures (grounding of equipment, tank shunts, lightning conductors, etc.) in poor condition are not effective in preventing an accident	Lightning protection measures must be well maintained and regularly checked.
	Existing lightning protection standards may not be sufficient to prevent the ignition of flammable substances in storage tanks	More research into the dynamics of direct and indirect lightning effects at chemical facilities is needed

* A scenario where a chemical accident in one industrial establishment triggers a secondary accident in the same or in one or more neighbouring establishments is referred to as domino effect

4 Conclusions

Earthquakes, floods and lightning have triggered a significant number of accidents in chemical and process installations, highlighting the vulnerability of chemical equipment and the potential for hazardous-materials releases. It is therefore indispensable that natural events be considered in the risk assessment of chemical installations in natural-hazard-prone areas to allow for adequate Natech prevention and mitigation measures to be put into place. Lessons learned from the present study show that the consequences of Natech accidents can be severe as the impact of natural events often results in multiple and simultaneous releases, increasing the likelihood of cascading effects. This applies especially to earthquakes and floods which usually hit large areas. Moreover, additional consequence scenarios for flood-triggered accidents were identified which should be considered in the risk assessment of chemical facilities located in flood zones.

The vulnerability of a specific equipment type and its failure modes were found to depend on the characteristics of the natural-hazard trigger. However, storage tanks and pipes are the equipment types most susceptible to damage and failure. This result is valid for all three types of considered natural events. It is therefore not surprising that the storage and transport of flammable substances frequently result in fires and explosions subsequent to the impact of a natural hazard or disaster. In the light of the results of the present study, a more detailed analysis of storage-tank and pipe behaviour under natural-event loading is

warranted. This will contribute towards the improvement or development of equipment vulnerability models, as well as to the definition of adequate protection systems and measures. In support of this objective, natural-hazard-specific key lessons learned were identified and accompanying recommendations on accident prevention and mitigation were provided.

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