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Industrial accidents triggered by lightning

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ABSTRACT

Natural disasters can cause major accidents in chemical facilities where they can lead to the release of hazardous materials which in turn can result in fires, explosions or toxic dispersion. Lightning strikes are the most frequent cause of major accidents triggered by natural events. In order to contribute towards the development of a quantitative approach for assessing lightning risk at industrial facilities, lightning-triggered accident case histories were retrieved from the major industrial accident databases and analysed to extract information on types of vulnerable equipment, failure dynamics and damage states, as well as on the final consequences of the event. The most vulnerable category of equipment is storage tanks. Lightning damage is incurred by immediate ignition, electrical and electronic systems failure or structural damage with subsequent release. Toxic releases and tank fires tend to be the most common scenarios associated with lightning strikes. Oil, diesel and gasoline are the substances most frequently released during lightning-triggered Natech accidents.

1. Introduction

Major accidents involving hazardous-materials releases in chemical facilities can be triggered by internal factors (e.g. technical failures or human errors) or by external threats, such as natural hazards or intentional acts. Recent studies have highlighted that natural events can cause severe loss of containment at chemical and process installations, triggering toxic dispersion, fires and/or explosions with potentially severe consequences [1–3]. As a result, fatalities and injuries, pollution, and business interruption with often severe economic losses have occurred. Accidents involving the release of hazardous materials (including oil spills) triggered by natural events are commonly referred to as “Natech” accidents [4].

While many different types of natural events have triggered Natech accidents, lightning strikes were the most common cause [5]. Rasmussen [6] analysed accident case histories in the industrial accident databases MHIDAS and FACTS and concluded that 61% of the accidents initiated by natural events at storage and processing activities were triggered by lightning strikes. Lightning was also found to be the most frequent cause of failure in the set of storage-tank accidents analysed in the study of Chang and Lin [7]. Storage tanks containing flammable substances are of particular concern in the presence of lightning risk as they represent a fire or explosion hazard in the event of a lightning strike.

Lightning can interact with an industrial structure either by direct strike, indirect lightning currents that induce secondary sparks, or by the disruption of control systems and electrical circuitry [8,9]. Direct lightning strikes can severely damage structures due to thermal heating. If flammable vapours are present, immediate ignition can occur. Major accidents have happened in the wake of direct or indirect lightning impact. For instance, in Dronka, Egypt, lightning struck a fuel depot during a rainstorm in 1994 and ignited the contents of eight tanks. The burning fuel flowed into a village where more than 400 people were killed [10]. In another case, lightning struck a floating-roof naphtha storage tank in Germany in 2001. Product vapour along the perimeter seal was immediately ignited [11]. In yet another example, lightning strikes resulted in power loss and subsequent power dips throughout the installation at the Pembroke refinery in the United Kingdom in 1994. Process-unit upsets led to the accidental release of a flammable mixture of hydrocarbons that was ignited by a heater. A vapour-cloud explosion and several fires followed, causing a downtime of 4.5 months and a loss of 10% of the total refining capacity in the United Kingdom [12].

In most cases, simple lightning protection measures, such as grounding or lighting rods, are implemented to reduce the risk of a lightning strike. However, several accidents suggest that these measures may not be sufficient to retain the structural integrity of equipment [13].

Despite the frequent occurrence of lightning-triggered Natech accidents, no specific risk assessment tool is available for this type of event, as e.g. those under development for Natech accidents triggered by earthquakes and floods [14–18]. In order to work

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towards filling this gap, in the present study the chain of events following lightning impact was analysed by studying industrial accidents. Therefore, case histories involving process and storage equipment containing hazardous substances were retrieved from the main industrial accident databases. The analysis aimed at the identification of vulnerable equipment categories, failure modes and damage states, and of final scenarios that can result as a consequence of lightning impact. This information is a starting point for the development of models and tools to be used in the quantitative assessment of lightning risk at chemical facilities.

2. Methodology for data retrieval and analysis

The data sources used for the present analysis were the European industrial accident databases ARIA [19], MHIDAS [20], MARS [21] and IChemE's The Accident Database (TAD) [22]. In addition, the US National Response Centre (NRC) database was interrogated [23]. The accident coverage in the databases is global with the exception of the NRC database where hazardous-materials-release and oil-spill reports are restricted to the United States and its territories. The analysed databases contain accident data from the open technical literature, government authorities, or in-company sources. Commonly, accident information from the chemical industry undergoes an abstraction process for confidentiality reasons. The ARIA and NRC databases are publicly available; access to MHIDAS, FACTS and TAD requires a license. The MARS database contains confidential information on major accidents submitted to the European Commission by the Competent Authorities. A detailed description of the analysed databases is presented elsewhere [2].

For the data extraction, selection criteria were defined in agreement with those used in a previous study on flood-triggered Natech accidents [2]. Therefore, the following criteria were used:

1. The loss of containment of a hazardous substance occurred or could have occurred.
2. An industrial activity having a relevant inventory of hazardous substances was involved.
3. The event generated or had the potential to generate an accident scenario with off-site consequences (major accident).

For the purposes of this study "hazardous substances" are chemicals that are classified in the European Dangerous Substances Directive [24] and its later amendments, including those that extended the Directive to mixtures of chemical substances [25]. The above selection criteria led to the inclusion in the analysis of industrial activities mainly falling under the provisions of the European Seveso II Directive on the control of major accident hazards [26] and similar legislation. However, accidents in industrial sites not covered by these types of legal frameworks were also included in the present study if they were considered useful for lessons learning.

The selection of accidents from the databases aimed at the collection of data belonging to the categories listed in Table 1. In addition, the following categories of process equipment were selected for the data analysis on the basis of the results of previous systematic studies on the taxonomy of process plants [27–29]:

- Storage: atmospheric or pressurized storage tanks, warehouses.
- Process: reactors, heat exchangers, columns, separators, others.
- Auxiliary: pipework, pumps and compressors.

Table 1
Categories of data retrieved from the industrial accident databases.

Substances involved
Equipment involved: category, geometrical data
Damage: type and extent of damage of involved equipment
Loss of containment: type, intensity, inventory involved
Accident scenario: events following release, final scenario
Safety barriers: safety barriers present, safety barriers effective
Consequences: extent of damage and loss of life

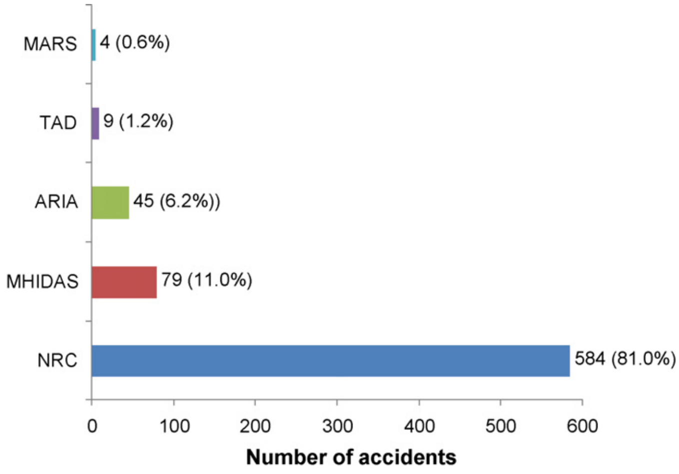

Fig. 1. Number of lightning-triggered Natech accident records retrieved and associated percent distribution with in the analysed accident databases.

Electric and electronic systems, as well as flare stacks were also considered as specific targets of lightning-induced accidents. Although their failure may not directly result in loss of containment of hazardous substances, secondary effects due to collapse or loss of utilities have the potential to trigger a major accident.

In accordance with the data-selection criteria discussed above releases from or fires in electrical transformers following a lighting strike were excluded from the analysis.

3. Results and discussion

3.1. General features of the available dataset

The application of the selection criteria discussed in Section 2 led to the retrieval of 721 lightning-triggered Natech events. The number of accidents extracted per each consulted database is shown in Fig. 1. In a few cases, the same event was reported in more than one database. Fig. 1 only makes reference to the source database where these accidents were reported in the most detail.

The quality of the reported information was often poor and in many cases the accident description was not very detailed or incomplete. Only limited data were reported on the type and extent of the structural damage suffered by the equipment involved and in several accident reports the chain of events leading to the loss of containment was not described. Moreover, the consulted industrial accident databases reported scarce, if any, data on the natural event that triggered the accident. However, this information is essential for relating the natural-event severity to the observed damage modes and states. Therefore, the analysis of specific issues of concern had to be limited to subsets of the retrieved 721 accidents which presented the necessary level of detail. In order to facilitate the future analysis of Natech accidents, the European Commission's Joint Research Centre has set up a dedicated Natech accident database to capture the specific characteristics of chemical accidents triggered by natural events [30].

3.2. Industrial activities and types of vulnerable equipment

A wide variety of industrial activities was found to have been involved in Natech accidents triggered by lightning strikes.

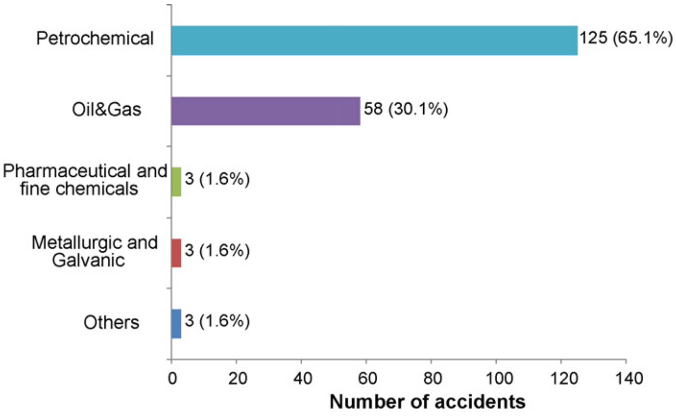

Fig. 2. Industrial activities involved in lightning-induced accidents with hazardous-materials releases (based on the analysis of a subset of 190 accident records).

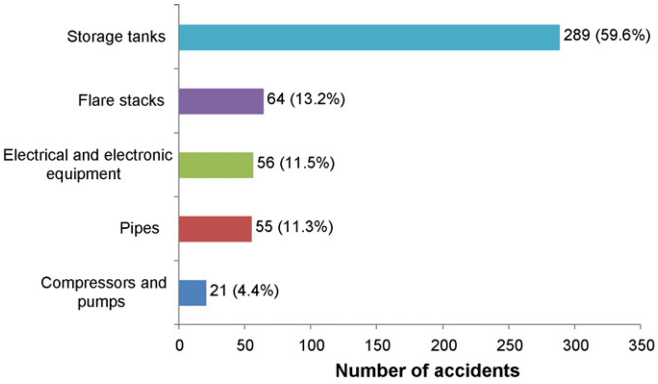

Fig. 3. Equipment categories involved in lightning-triggered Natech accidents (based on 485 accident records).

Fig. 2 gives an overview of the industrial sectors for which accidents were recorded in the analysed databases. According to the data (a subset of 190 accident records that provided the required information) 91% of lightning-triggered Natech events occurred in oil and gas facilities (mainly oil refineries) and the petrochemical sector, including storage sites and tank farms. These results are obviously influenced by the large number of industrial sites in operation within these sectors, as well as by their susceptibility to lightning. However, the high vulnerability of equipment categories present in such facilities is evident.

The equipment categories most frequently damaged by lightning strikes are shown in Fig. 3, which is based on the analysis of 485 accident records. Storage tanks are the equipment category most frequently affected by lightning impact. Atmospheric tanks, and in particular floating-roof tanks which are commonly used for the storage of liquid hydrocarbons, are the most vulnerable equipment. They are usually high-capacity tanks and can initiate accident scenarios with significant severity should they undergo failure with loss of containment. Pressurised tanks are less frequently involved in accidents with loss of containment possibly due to their more robust design and higher shell thickness. Only 3 out of 289 accidents involved pressurised storage tanks.

Other categories of process equipment were less susceptible to the impact of lightning. Compressors and pumps were affected in 21 events, while only 4 accident records reported damage to distillation columns. In contrast, flare stacks, pipes and electrical devices showed a high vulnerability to damage from lightning. Although lightning strikes on flare stacks appeared to result in very limited or no loss of containment, in a few accidents structural collapse of the flare stack caused damage to other types of equipment.

Lightning impact also resulted in the disruption of control systems and electrical circuitry which led to corrupted data, false signals, and damage to sensitive electronic devices. Several loss of containment events were reported as a consequence of this type of lighting-induced damage.

3.3. *Failure modes and damage states*

There is only limited information on the structural damage to equipment due to the impact of lightning. The failure modes that equipment may be subject to during a lightning strike are described only in very general and qualitative terms in the analysed accident databases. From the limited information reported, two different failure modes were identified, which are direct and indirect structural damage. Structural damage due to a direct lightning strike was observed in several events. Indirect structural damage was also reported due to the collapse of structural elements that resulted in damage to process equipment (e.g. flare stacks that collapsed over process units).

A qualitative approach was used to characterise the equipment damage modes following a lightning strike. As in the case of earthquake and flood damage [17,18], three “damage states” (DS) were defined. Three associated “release states” (R) were also introduced to characterise the intensity of loss of containment that may follow equipment damage. A detailed description of damage states and release states is provided in Table 2.

In addition to loss of containment caused by structural damage, two further categories of events were often triggered by lightning. These are damage to electric and electronic systems and immediate ignition of flammable substances. In several cases the electric field generated by the lightning caused the failure of control devices. This resulted in loss of containment from vent and blow-down systems. Immediate ignition of flammable substances at the rim seal of storage tanks was also reported to have caused several fires and explosions. Table 3 summarises the damage states recorded for 172 accidents involving storage tanks as a consequence of lightning strike, and the associated release categories.

Table 2
Defined damage states and associated of release states.

Damage state (DS)	DS1	DS2	DS3
Definition	Extended structural damage or collapse of the unit	Severe damage to the unit that retains its structural integrity but suffers extended failures (e.g. full-bore rupture of large diameter connections or shell rupture)	Minor damage to the unit (e.g. partial failure of connections or full-bore rupture of small-diameter pipes)
Release state (R)	R1	R2	R3
Definition	Possible sudden release of entire inventory	Possible release of the complete inventory in a limited time lapse (e.g. 2–20min)	Minor leaks (e.g. release from a 10mm equivalent diameter)

Table 3
Damage and release states observed for storage tanks damaged by lightning based on the analysis of 172 accident records.

Type of event	Number of records	Damage state	Release state
Electrical device malfunctions	9	–	–
Confined explosion[a]	36	DS1	–
Pipework detachment	1	DS3	R3
Pool fire	116	DS2–DS3	R2–R1
Roof fire[a]	10	DS1	–

[a] Entire inventory involved in explosion or fire; only post-accident release can take place.

Table 4
Hazardous substances released during 713 lightning-triggered Natech accidents.

Substance category	Hazard	Number of accidents
Oil, diesel and gasoline	Extremely flammable	389
Oxides	Explosive	122
Natural gas	Extremely flammable, Explosive	105
Aromatics	Extremely flammable; dangerous for the environment	34
Chlorine	Toxic; dangerous for the environment	32
Ammonia	Toxic; dangerous for the environment	19
Acid products	Toxic; dangerous for the environment	10
Cyanides	Toxic; dangerous for the environment	1
Explosives	Oxidising	1

3.4. Accident scenarios

Accidents with hazardous-materials releases triggered by lightning have the potential to result in severe off-site consequences. This is due to the fact that storage tanks, which are the most vulnerable equipment category, usually contain large amounts of flammable substances. In fact, the hazardous substances mainly involved in this type of Natech accident were found to be oil, diesel and gasoline which are normally stored in atmospheric storage tanks. Table 4 gives an overview of the released substances and the number of accident records associated with each. In addition, the table also includes the hazardous properties of the released substances based on the general hazard classification according to the European Directive on the classification and labelling of dangerous substances [24]. Using a subset of 335 accident records the released quantities were estimated. As shown in Fig. 4, the amount of hazardous substances released was in the range of 100–1000 kg in 35% of the considered accident records and exceeded 1000 kg in 38% of the recorded events.

The accident scenarios initiated by a lightning strike are influenced by the type of equipment damaged, the substance inventory and the operating conditions. Fig. 5a shows the consequences of accidents in which equipment damage led to a release of hazardous substances. The analysis of the accident case histories clearly shows that the majority of lightning-triggered events resulted in the release of hazardous substances (58%). A lower number of accidents resulted in fires (35%) and explosions (7%). Toxic cloud dispersion is also a possible consequence. However, this was explicitly indicated in three accident records only.

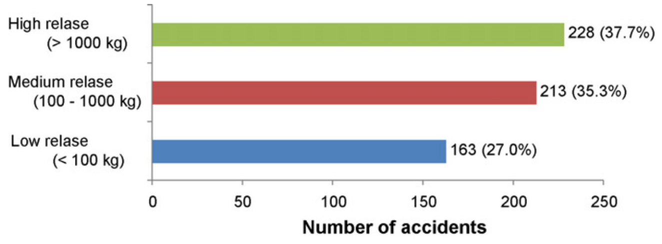

Fig. 4. Released quantities of hazardous materials during lightning-induced Natech events (335 records).

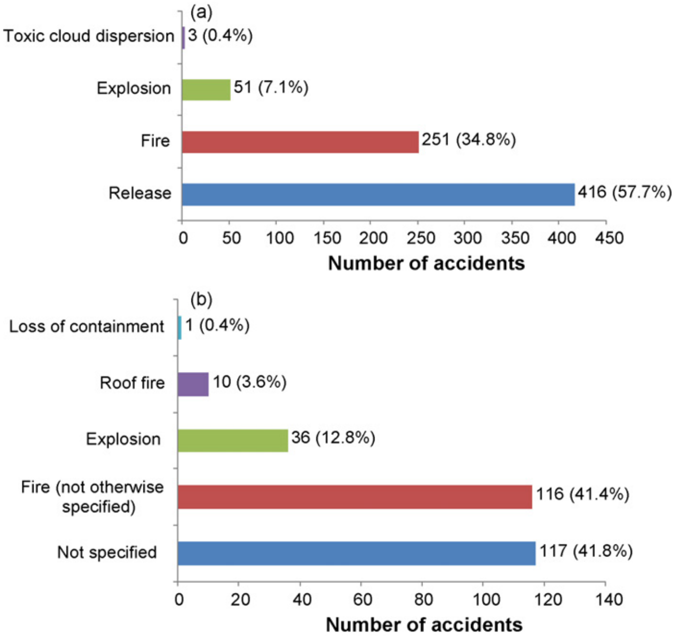

Fig. 5. Accident scenarios initiated by lightning strikes. (a) Data on 721 events analysed. (b) Specific data on 280 events involving storage tanks.

Several accident records provided more detailed information on the specific type of damage suffered by storage tanks. As shown in Fig. 5b, the final scenarios most frequently observed for this equipment category were fires and explosions. The final scenarios following a lightning strike depend on the geometrical and mechanical properties of the tank, its inventory, the lightning attachment point, the safety and protection measures implemented, and on other simultaneous events that may have taken place (e.g. flooding due to heavy rain). In 10 accident records the tank roof is indicated as the location of the fire, while most records do not provide this information. It is highly likely that ignition in atmospheric floating-roof tanks occurs at the rim seal of the floating roof where flammable vapours may be present. A detailed description of the types of fires reported for storage tanks in the analysed accident records as a consequence of lightning impact is shown in Table 5.

The analysis of several accident reports provided information on the sequence of events triggered by the lightning strike, starting at loss of containment and leading to the recorded final scenario. The available data were used to develop substance-specific event trees for use in quantitative risk assessment. Therefore, a release state as defined in Table 2 was associated with each of the analysed accident records. The conventional categories of final scenarios adopted in the scientific literature (e.g. see reviews provided by the “Purple Book” [27], CCPS [31], and Lees [32]) were used as end points for the event-tree development. Post-release events derived from the analysis of the available case histories were categorised and used for the development of the event-tree structure. A validation of the final structure was carried out verifying that each of the event sequences identified in the developed event trees occurred in at least one of the retrieved accident case histories.

Fig. 6 shows the event trees obtained for flammable substances, while Fig. 7 shows those developed for liquid or gaseous substances that are toxic or dangerous for the environment. As evident from Fig. 6, the post-release event trees for flammable substances are quite similar to those obtained for the consequence of internal

Table 5
Detailed description of the types of fires observed after a lightning strike on storage tanks.

Type of event	Description
Bund fire	Occurs within the containment area outside the tank shell. It can range from a small spill incident (from tank fittings, flanges and associated pipework) up to a fire covering the whole of the bund area. In the presence of a flammable mixture, fire may result due to the ignition source represented by lightning.
Rim-seal fire	Occurs when the flammable vapours find ignition in the seal area between the tank shell and the roof that has lost integrity. The amount of seal involved in the fire can vary from a small localised area up to the full circumference of the tank.
Spill-on-roof fire	Occurs when a hydrocarbon spill on the tank roof is ignited by lightning but the roof maintains its buoyancy. In addition, flammable vapours escaping through a tank vent or roof fitting may be ignited.
Full surface fire	Occurs when the tank roof has lost its buoyancy and some or the entire surface of liquid in the tank is exposed and then involved in the fire.

failures. As shown in Fig. 7, the possible release of liquid toxic or environmentally hazardous substances from catch basins was explicitly introduced in the event tree as suggested by the results of the accident analysis. While the release from catch basins has a very low probability under normal operating conditions, this is not the case for lightning-triggered releases. As lightning is usually accompanied by heavy rainfalls, the probability of a release from the tank basin is rather high, either due to the overfilling of the catch basin caused by rainwater or because of a possible release from the catch-basin drainage system. As reported in several of the collected accident case histories, during heavy rainfalls the capacity of the drainage water segregation system may be exceeded, and drainage water may be released to the environment bypassing the water treatment system.

A scenario involving the formation of toxic or flammable vapours due to the reaction of the released substances with rainwater was reported in a few accidents analysed in this study. This final scenario was also observed for flood-triggered Natech accidents in a previous study [2]. However, due to its very specific nature, this scenario was not included in the reported event trees. No events involving the release of solid materials were present in the analysed dataset.

Table 6
Available data for number of damaged tanks, number of releases and ignition probability for storage tanks damaged by lightning (data from the analysis of 252 accident records related only to flammable substances).

Number of lightning events	252
Number of damaged storage tanks	399
Maximum number of damaged storage tanks in a single event	27
Medium number of damaged storage tanks in a single event	1.6
Number of damaged storage tanks with release	241
Number of cases of release with ignition	198
Ignition probability	0.82

In order to understand how frequently ignition occurred during lightning-triggered releases of flammable substances from storage tanks, a subset of 252 accident records involving flammable substances was analysed. The results, shown in Table 6, provided interesting insights into the average number of damaged storage tanks per lightning strike and the maximum number of damaged tanks in a single lightning event. An ignition probability of 0.82 was estimated from the data analysis. This number is likely to be an upper limit as a reporting bias towards high-consequence accidents was observed.

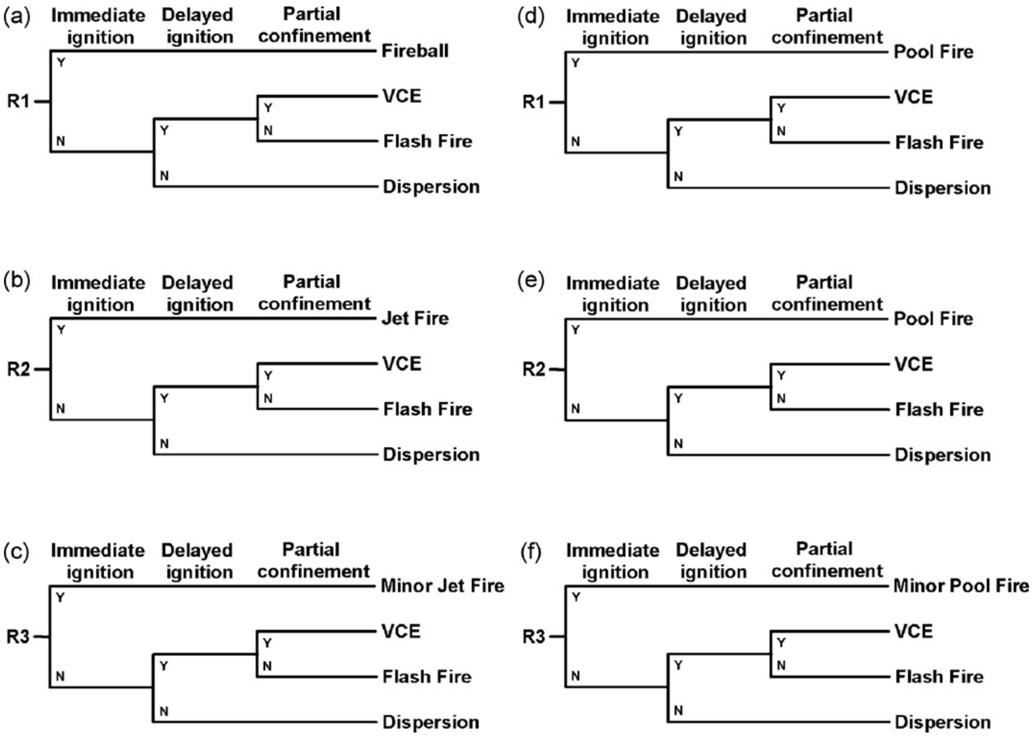

Fig. 6. Post-release event trees for flammable substances developed from the analysis of accident case histories as function of the release category. (a) R1, pressurized; (b) R2, pressurized; (c) R3, pressurized; (d) R1, non-pressurized, (e) R2, non-pressurized; (f) R3, non-pressurized. VCE: vapour-cloud explosion.

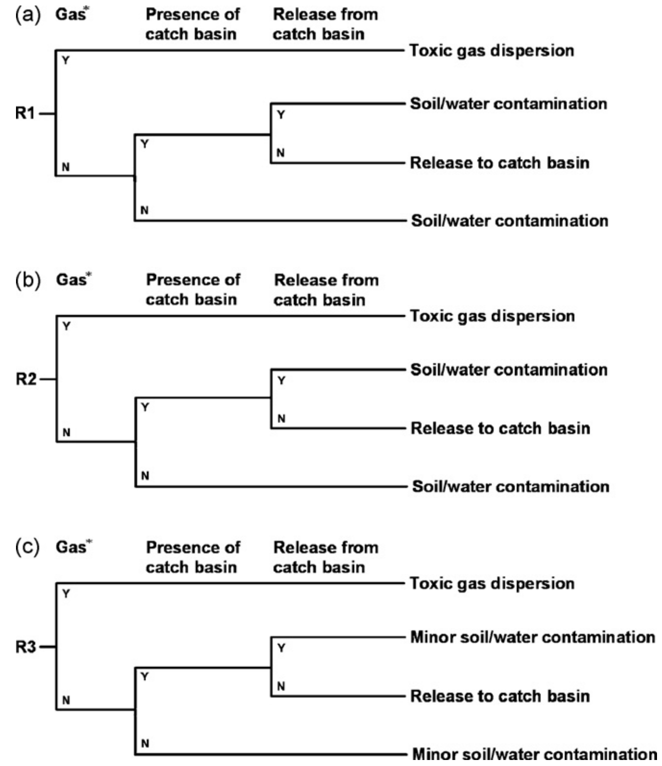

Fig. 7. Post-release event trees for gaseous or liquid toxic substances in Natech accidents triggered by lightning developed from the results of the performed accident analysis. (a) R1 release state; (b) R2 release state; (c) R3 release state (* at ambient temperature and atmospheric pressure).

Limited information on the on- and off-site consequences of lightning-triggered accidents was provided in the analysed databases. In 6 out of 721 records fatalities were reported. The two most severe accidents analysed resulted in over 400 and 16 fatalities, respectively. In 11 accident case histories information on the number of injured people was provided. In two cases more than 70 people were injured, while in two further accidents over 20 injuries were reported. In 34 accident records workers and/or residents were evacuated in accordance with site-internal or external emergency plans. Details on disruption of community life following the accident were provided for 16 accident records. These included lighting-triggered pollution of aqueducts, disruption of water or power supply, and the closure of roads and public buildings.

Information on the direct and indirect costs of lightning-triggered accidents indicates that the economic losses are significant. This is due to structural and non-structural damage but also to the costs of the emergency response operations, as well as to business interruption and loss of production. In some cases the costs of the accident also concerned damages to houses and private property outside the plant limits. In only 23 accidents records the economic losses were specified. The most costly reported Natech accident triggered by lightning resulted in damage of the order of 140 million US$ (in 1994 Dollars [20]).

4. Conclusions

Data on accidents triggered by lightning in industrial facilities were collected and analysed. The results provided useful information on the equipment categories most vulnerable to lightning impact. Information on damage to and release modes of equipment impacted by lightning was also obtained. The analysis of accident reports allowed the identification of damage states and the definition of the expected release classes following the impact of lightning. Data on final scenarios highlighted the importance of specific phenomena due to the likely presence of heavy rainstorms during lightning strikes. An ignition probability for released flammable substances was estimated from the analysed data and specific post-release event trees were developed. Thus the results of the present study support the development of specific tools for the quantitative risk analysis of Natech accidents triggered by lightning.

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