Journal of Hazardous Materials 183 (2010) 565–573

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Domino effect in chemical accidents: Main features and accident sequences

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ARTICLE INFO

Article history:
Received 21 May 2010
Received in revised form 7 July 2010
Accepted 13 July 2010
Available online 21 July 2010

Keywords:
Domino effect
Accident sequence
Major accident
Historical analysis
Risk analysis

ABSTRACT

The main features of domino accidents in process/storage plants and in the transportation of hazardous materials were studied through an analysis of 225 accidents involving this effect. Data on these accidents, which occurred after 1961, were taken from several sources. Aspects analyzed included the accident scenario, the type of accident, the materials involved, the causes and consequences and the most common accident sequences. The analysis showed that the most frequent causes are external events (31%) and mechanical failure (29%). Storage areas (35%) and process plants (28%) are by far the most common settings for domino accidents. Eighty-nine per cent of the accidents involved flammable materials, the most frequent of which was LPG. The domino effect sequences were analyzed using relative probability event trees. The most frequent sequences were explosion → fire (27.6%), fire → explosion (27.5%) and fire → fire (17.8%).

1. Introduction

When a major accident occurs in a process plant or a storage area, its physical effects (overpressure, thermal flux, impact of missiles, etc.) often damage surrounding equipments. In some cases the affected equipment fails, which can lead to loss of containment and an additional accident scenario: for example, the flames of a jet fire impinge on a vessel causing it to explode, or a fragment ejected by an explosion impacts on a pipe causing loss of containment of a flammable liquid and subsequent ignition. Therefore, a relatively minor accident can initiate a sequence of events that cause damage over a much larger area and lead to far more severe consequences. This is usually called a *domino effect*.

A domino effect can occur in a variety of ways, although an essential aspect is whether it involves a single plant or progresses from one plant, where the accident took place, to others. According to this criterion, Reniers [1] classified domino effects into two categories: internal domino and external domino. In internal (single-company) domino effects, the escalation of an accident occurs inside the boundaries of a chemical plant; in external (multi-company) domino effects, one or more secondary accidents occur outside the boundaries of the plant where the primary event occurs.

External domino effects often have more severe consequences than internal domino effects, as the affected area is greater and more equipment is involved. However, they have received less attention than internal domino accidents [1] because they are less frequent, their modeling is highly complex, and they are difficult to investigate because several companies are involved.

A number of domino effect definitions have been proposed. Reniers [1] has published 13, some are very concise, such as "an event at one unit that causes a further event at another unit" [2], and others are more complex. Most of these definitions contain the following three concepts:

1. A "primary" event (fire, explosion) that occurs in a certain unit.
2. The propagation of the accident to one or more units or plants, in which "secondary" accidents are triggered as a result of the primary event.
3. An "escalation" effect that leads to a general increase in consequences, with secondary accidents being more severe than the primary one.

Among the various definitions that have been proposed for the domino effect, the following one by Delvosalle [3] covers these three aspects and seems suitable for the purpose of this survey: "*a cascade of events in which the consequences of a previous accident are increased both spatially and temporally by the following ones, thus leading to a major accident*". Therefore, this is the definition used as a framework for the selection of accidents.

Fires are the most frequent accidents in industrial installations, followed by explosions and gas clouds. A recent historical analysis [4] showed that in sea port areas, 59.5% of accidents were fires, 34.5% were explosions and 6% were toxic clouds. A survey of accidents occurring during the transport of hazardous substances by road and rail [5] showed that 65% were fires, 24% were explosions and 11% were gas clouds. Gas clouds have little impact on domino

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doi:10.1016/j.jhazmat.2010.07.061

effect scenarios, but fires and explosions can easily cause subsequent accidents, and their physical effects can trigger a domino sequence. The severity of the ensuing scenario can be increased considerably by the influence of a domino effect.

The most common primary phenomena leading to additional – and, in many cases, more severe – equipment failure are jet flame impingement, pool fires (flame impingement or radiation), vessel or vapor cloud explosion blasts, and impact of explosion missiles. Although these phenomena can occur in any industrial installation, congested plants such as offshore platforms or process plants, where processing equipment and control systems are in proximity, are especially prone to these types of primary event. Storage areas, which usually contain large amounts of hazardous materials, are also common settings for domino effect scenarios.

The domino effect is a highly important phenomenon in the process industry and was specifically addressed in the first version of the Seveso Directive (European Council Directive 82/501/ECC) [6]. Subsequent versions, Directive 96/82/EC [7] and Directive 2003/105/EC [8], stipulated that domino effect hazards must be assessed inside and outside industrial installations. The domino effect is an important aspect in risk analysis, as knowledge of the main hazards and features of this phenomenon can be used to identify additional safety measures, such as the minimum safe distances between certain types of equipment.

Several authors have analyzed the aspects involved in domino accidents. Bagster and Pitblado [9] and Khan and Abassi [10] analyzed their frequency and likelihood. Cozzani and Salzano [11] studied the contribution of blast wave as a primary event and proposed threshold values for process equipment and probit models [12] for different equipment categories. Antonioni et al. [13] developed a methodology for quantitatively assessing the contribution of domino effects to overall risk in an extended industrial area. Reniers et al. [14] analyzed the efficiency of current risk analysis tools for preventing external domino accidents. The same authors [15] proposed a technical framework that integrated three risk analysis methodologies for preventing external domino accidents. Cozzani et al. [16] emphasized the importance of combining inherent safety criteria with conventional active and passive protection.

Few authors have published historical surveys of the domino effect. Among them, Kourniotis et al. [17] examined a set of 207 major chemical accidents that occurred between 1960 and 1998, 114 of which involved a domino effect according to their criteria. The authors analyzed the likelihood or relative probability of accidents with one or two domino effect sequences with respect to the total number of accidents involving substances in four categories (liquid fuels, vapor hydrocarbons, toxic substances and miscellaneous substances). They also studied the severity of the consequences on the affected population using *p*–*N* curves and a modified version of the Pareto distribution. According to the data published by Kourniotis et al., the ratio between the number of accidents involving one domino effect (80) and the number of accidents involving a sequence of at least two domino effects (34) was 2.3.

Ronza et al. [18] performed a survey of 828 accidents in port areas. They constructed relative probability event trees to analyze the sequence of the 108 accident scenarios in which a domino effect was observed and found the most frequent sequences to be fire → explosion, release → fire → explosion, and release → gas cloud → explosion. Gómez-Mares et al. published a specific study of accidental scenarios involving jet fires [19]. They identified 84 accidents involving this phenomenon and found that in 50% of them jet fires had been the primary event of a domino sequence. Abdolhamidzadeh et al. [20] studied a set of 73 domino accidents that occurred between 1910 and 2008 and analyzed the type of activity, the substances involved, the level of domino effect and the impact on the affected population. The study focuses on a relatively small number of accidents, some of which occurred in the early 20th century. Since then, industry and transportation have changed considerably. However, the ratio between first-level and second-level domino sequences (2.2) is very similar to the value obtained by Kourniotis et al. [17].

Although the above studies provide useful information, they either focus on very specific scenarios [18,19] or overlook the different sequences through which the domino effect occurs [17,20]. Consequently, in this study, information was compiled on a large number of accidents, and relative probability event trees were constructed to perform a more exhaustive historical analysis. The different scenarios in which the domino accidents occurred, including fixed installations and transportation, are presented. The specific case of transfer (loading/unloading) is also considered. Aspects such as the accident scenario, the causes, the types of materials involved, the effects and consequences, the affected population, and the probability of specific accident sequences are analyzed. Finally, a series of conclusions are drawn on the occurrence of these accidents and the possibility of applying specific safety measures to reduce their probability.

2. Methodology and selection criteria

The main source of information for this survey was the Major Hazard Incident Data Service (MHIDAS) database [21] (November 2007 version, containing 14,168 records), managed by the UK Health and Safety Executive. The database covers incidents recorded during the 20th century in over 95 countries. All of the information is taken from public-domain sources, and each record is categorized by the field in which it occurred to facilitate automatic processing. The following databases were also consulted: the Major Accident Reporting System (MARS) [22], through which EU member states report industrial accidents in a standard format, overseen by the Major Accident Hazards Bureau (MAHB) of the European Commission Joint Research Centre; the Failure and Accidents Technical Information System (FACTS) [23], a database for accidents involving hazardous materials created by TNO Industrial and External Safety (the Netherlands) in the late 1970s; and the *Analyse, Recherche et Information sur les Accidents* (ARIA) database [24], created in 1992 by the French Ministry of Regional Planning and the Environment. The information in these databases on specific accidents is often incomplete and they contain few data on the accident sequence or its consequences. Therefore, a detailed search for specific information on most accidents was conducted by consulting accident reports and Internet sources.

During the study of the MHIDAS database and the other sources mentioned above, the following accident scenarios were considered: processing, loading/unloading, transportation (by rail, road and sea) and storage. Accidents caused by natural events were also taken into account. To work more efficiently, the information taken mainly from the MHIDAS database was transferred to an Access database created specifically for the study.

Taking into account the scenarios mentioned above, a selection of the accidents was made using keywords related to the domino effect. A second filter was then applied to exclude those incidents triggered by sabotage or terrorist action and those involving military equipment or conventional explosives; as these were considered to be exceptional circumstances that would not usually be encountered in industrial activities.

One of the critical tasks in the preparation of this historical analysis was to set the criteria for differentiating domino accidents from non-domino accidents. The first step was to establish a clear definition of the domino effect itself [3] (see Section 1), as the one chosen in the introduction is open to diverse interpretations, particularly the use of the term “temporally”. The definition was limited with the following criteria:

- If an accident occurs and, as a result, another accident (secondary event) occurs temporally or spatially, the scenario is considered a domino effect.
- When an accident occurs and causes a secondary gas or liquid release that has no additional consequences, it is not considered a domino effect (a secondary release without effects and consequences is not considered an accident, but rather an incident). One example is a flammable cloud that is not ignited and is dispersed into the atmosphere. However, if the secondary event produces a toxic cloud, which will have an effect on a given zone and may have consequences, the scenario is considered a domino effect.

These criteria were applied to the accidents compiled from the databases as the third level of selection for this study, which required an exhaustive case-by-case analysis. Only accidents that occurred over the past 50 years were taken into account. Accidents that occurred prior to 1961 were excluded, as they happened in another technological environment in which safety measures and risk planning were not comparable with those currently in place. This reduced the number of accidents studied but increased the quality and significance of the sample. The additional filter gave a total of 225 accidents, which is a much larger sample than those analyzed in previous studies [17–20].

3. Distribution of accidents over time

The number of accidents increased between 1961 and 1970–1980 (Table 1). This has two main explanations. Firstly, the chemical industry has grown continuously since the early 1960s: more and larger process plants and storage areas have been built, leading to an increase in the transportation of hazardous materials. Secondly, access to information on industrial accidents has improved gradually over time; a considerable number of accidents that occurred during the 1960s were not recorded and the information was lost.

Most historical analyses therefore report a dramatic, continuous rise in the frequency of major accidents over the past 50 years (see, for example, the analyses performed in [4,5]). However, in this case the peak accident rate was reached in the late 1970s and the 1980s, after which there was a continuous decrease until 2007. This decreasing trend was not expected, but it is in good agreement with data published recently by Gómez-Mares [25] and Niemitz [26]. Niemitz analyzed the major accidents registered in the EU's Major Accident Reporting System (MARS) [22] between 1996 and 2004, and also found a decreasing trend (Fig. 1).

The decreasing accident rate since 1990 could be explained by general improvements in the safety culture of the chemical industry brought about by strict new regulations (e.g. EU directives) and more effective operator training; for example, prompt action in the event of an accident could prevent propagation and the development of a domino effect. The increasing automation of industrial facilities may also have helped to reduce the number of domino accidents. Nevertheless, the trend is surprising and should be monitored over the coming years.

Table 1
Frequency of occurrence.

Period	No. of accidents	%
1961–1970	49	22
1971–1980	70	31
1981–1990	63	28
1991–2000	24	11
2001–2007	19	8

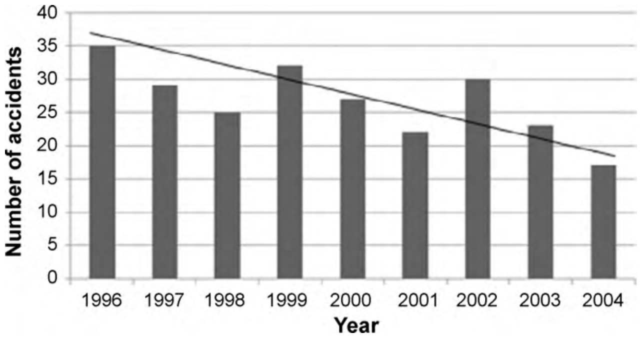

Fig. 1. Trend of the frequency of major accidents in EU-15 (1996–2004) according to data registered in MARS (taken from Niemitz [17]).

4. Accident location

Accidents were divided into three categories according to the country in which they occurred:

1. The European Union (25%) (accidents in countries that have since joined the EU are not included in this category).
2. Other developed countries: Australia, Canada, Japan, New Zealand, Norway and the United States (56%).
3. The rest of the world (19%).

A certain degree of bias may exist because preference was given to information on accidents that occurred in Europe and the United States (most of the institutions that manage the databases used in the study are based in these countries and the information on them is generally more exhaustive). Nevertheless, the general trend shown by the data should be accurate.

More than 80% of the accidents involving a domino effect occurred in developed countries. The massive presence of large-scale plants and the associated transportation and storage infrastructures in these countries accounts for the high percentage, although some loss of data in the rest of the world must be considered. Using the selection filters explained above (Section 2), a specific case could be excluded from the study if insufficient information is available. Given that information on industrial accidents in developing countries is more likely to be incomplete, the selection process is more likely to exclude accidents from these countries.

5. Materials involved

The accidents generally involved more than one substance. In total, 375 substances were identified in the 225 accidents. However, the real number of substances was higher, as in some accidents only the substance involved in the primary accident was specifically mentioned, and sentences such as "the fire spread to storage tanks containing chemicals" were occasionally used to describe the secondary accident. A relatively small number of accidents involved only one substance (for example, propane was involved in a series of fires and explosions in a propane gas farm).

Flammable substances were involved in most of the accidents (89%) and were the substances most frequently found in domino accidents (Table 2). LPG is by far the most frequent (60 cases, 27%), and many of the cases in which it was recorded were transportation accidents. Oil and gasoline were found in approximately the same number of the accidents considered (11% each one), followed by naphtha (6%) and diesel oil (5%). Chlorine was found in 3% of cases, and ammonia in only 2% of cases.

Table 2
The substances most frequently involved.

Substance	No. of accidents	%
LPG	60	26.7
Oil	25	11.1
Gasoline	24	10.7
Naphta	14	6.2
Diesel oil	12	5.3
Toluene	9	4.0
Vinyl chloride	9	4.0
Ethylene	8	3.6
Ethylene oxide	7	3.1
Natural gas	7	3.1
Chlorine	7	3.1
Methanol	6	2.7

6. Causes

The cause of the primary accident is an important aspect in the analysis of domino effect accidents. Although the information came from a variety of sources, the MHIDAS database categories were used for the generic causes: external events, mechanical failure, human error, impact failure, violent reaction (runaway reaction), instrument failure, upset process conditions and services failure.

Although some of the generic causes are self-explanatory (for example, violent reaction), human error is more complex because other causes such as violent reaction or mechanical failure could themselves be caused by human error. For the purposes of this study, only those cases in which specific reference to human error was made were classified as such; however, the figure obtained for this cause is probably lower than the real value and a higher percentage could be assumed.

The generic causes that initiated a domino accident in the cases included in this analysis are shown in Table 3. The percentages do not total 100 because some accidents were triggered by more than one generic cause. External events (31%) and mechanical failure (29%) were the main causes. Human error caused 21% of the accidents, which is a similar value to the one obtained by Vílchez et al. [27], who found that 24% of the 4155 accidents analyzed in their study (both in fixed installations and in transportation) occurred as a result of human error.

The specific causes are shown in Table 4; again, the overall number is higher than 225 because some of the accidents had more than one simultaneous cause. Of the external causes, accidents (fire and explosion) in other plants were the most frequent types. When the primary event was an explosion, it was usually impossible to ascertain from the information available whether it was the blast wave or the fragment projection that caused the secondary accident. When human error was the generic cause of the accident, general operations, general maintenance, overfilling and procedural failures were the main specific causes. In accidents initiated by impact, rail accidents were the main specific cause (72%).

Table 3
General causes of the accidents.

Cause	No. of events	%
External events	69	30.7
Mechanical failure	65	28.9
Human factor	47	20.9
Impact failure	40	17.8
Violent reaction	21	9.3
Instrument failure	8	3.6
Upset process conditions	5	2.2
Services failure	3	1.3

Table 4
Specific causes of the accidents.

General cause	Specific cause	No. of accidents	% of category
External[a] (84)	Fire	45	54
	Explosion	25	30
	Lightning	10	12
	Flooding	1	1
	Sabotage or vandalism	1	1
	Temperature extremes	1	1
	Earthquake	1	1
Human (45)	General operations	10	22
	General maintenance	9	20
	Overfilling	7	16
	Procedural failures	7	16
	Design error	5	11
	Draining accident	2	4
	Failure to isolate or drain before uncoupling	2	4
	Accidental venting	1	2
	Failure to connect/disconnect	1	2
	Management	1	2
Impact (46)	Rail accident, no other vehicle	28	72
	Other vehicle	6	15
	Heavy object	4	10
	Ship to ship collision, barges	1	3
Instrument (8)	Controller	4	50
	Trip related failure	3	37
	Indicator failure	1	13
Mechanical (59)	Overheating	9	15
	Overpressure	9	15
	Leaking coupling or flange	7	12
	Hose failure	6	10
	Other metallurgical failure	6	10
	Relief valve failure	4	7
	Leaking or passing valve	3	5
	Leaking gland or seal	3	5
	Weld failure	3	5
	Corrosion	3	5
	Fatigue	3	5
	Brittle failure	1	2
	Use of incompatible materials	1	2
	Overloading	1	2
Service (3)	Electricity	2	67
	Water supply	1	33
Violent reaction (15)	Runaway reaction	8	53
	Confined explosion	7	47

[a] The number of accidents in this category ("External") is higher than the that shown in Table 3 since there are some accidents that have more than one specific cause inside this general cause.

7. Origin

The MHIDAS database uses the following categories to designate the place or activity in which the accident occurred: process, storage, transportation, transfer, commercial and warehouse. As shown in Fig. 2, the most critical area is storage (35%), followed by process plants (28%) and transportation (19%). In storage areas, the presence of tanks containing hazardous materials (often flammable) increases the probability of a domino effect in the event of a fire or explosion. The same effect is observed in process plants due to their compact design.

Transfer is a very interesting case. Transfer operations, such as loading/unloading, are known to be highly hazardous activities and are involved in 13% of all domino accidents. This figure is in good agreement with the values reported in other historical analyses: Gómez-Mares et al. [19] found that 11% of accidents involving jet

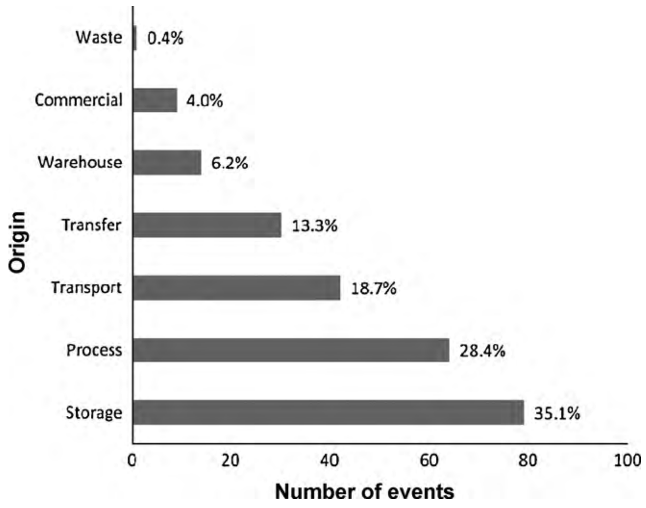

Fig. 2. Origin of the accidents (accidents in loading/unloading operations are included in “transfer”).

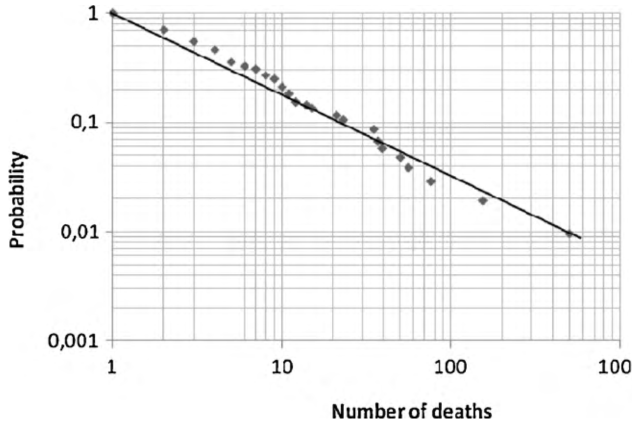

Fig. 3. Accumulated probability as a function of the number of deaths.

fires and domino effects were initiated by loading/unloading operations; Vílchez et al. [27] found that 8% of all accidents occurred during these operations.

8. Affected population

The population affected by industrial accidents can be classified into three categories according to the severity of the consequences: number of fatalities, number of injured and number of evacuees. Information on human consequences was not available for all of the accidents surveyed (the number of fatalities was given for 82% of accidents, injured for 67%, and evacuees for 38%).

Of the accidents for which information on fatalities was available, 43% caused no reported deaths. Of the remaining accidents, 47% caused 1–10 deaths, 9% caused 11–100 deaths, and 2 accidents (1%) caused over 100 deaths. The accident that caused the highest number of fatalities occurred in San Juan Ixhuatepec (Mexico, 1984), where a series of explosions and fires destroyed a large number of cylindrical and spherical vessels in an LPG storage area, killing 503 people [28].

The best way to represent the lethality of accidents is probably the *p*–*N* curve (Fig. 3). In the figure, the abscissae represent the severity of the accident (the number of fatalities, *N*) and the values on the ordinate axis represent the probability (*p*) that an accident with casualties will cause a number of fatalities equal to or greater than *N* (for $N = 1$, $p = 1$). For all accidents, the best fit (least squares method) for a curve $p = N^b$ gives $b = -0.74$, which means that the probability of an accident involving a domino effect that causes 10 or more deaths is 5.5 ($=10^{-b}$) times greater than the probability of a domino accident that causes 100 or more deaths. This *b* value is lower than the global figure $b = -0.84$ reported by Vílchez et al. [27] for all accidents (with or without a domino effect), indicating that accidents involving a domino effect have slightly more severe consequences on the affected population. Kourniotis et al. [8] found similar results.

Fig. 4 shows a *p*–*N* plot of the accidents according to the geographical location in which they occurred. The severity of accidents in the European Union and in Australia, Canada, Japan, New Zealand, Norway and the USA (other developed countries) was considerably lower than that of accidents in the rest of the world.

In 31% of accidents there were no injuries, in 39% there were between 1 and 10, in 26% there were between 11 and 100, and in only 6 cases (4%) were there more than 100. The accident with the highest number of injured was also the San Juan Ixhuatepec accident, described above, which caused injury to approximately 3800 people.

Analysis of the number of evacuees revealed a fairly homogeneous distribution: in 19% of accidents there were no evacuees, in 27% there were between 1 and 100, in 25% there were between 101 and 1000, in 26% there were between 1001 and 10,000, and in only 4% were there more than 10,000. The worst cases led to the evacu-

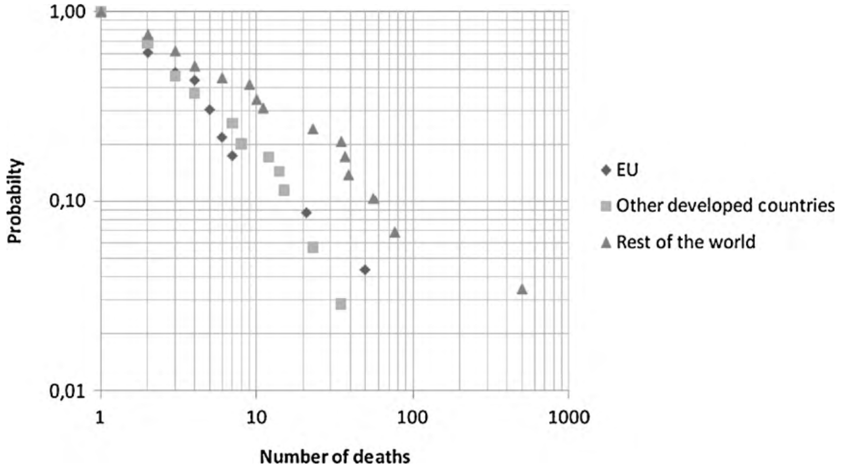

Fig. 4. *p*–*N* curves as a function according to the development degree of the countries.

ation of 200,000 people (San Juan Ixhuatepec) and 100,000 people (Visakhapatnam, India, where a leaking pipe caught fire during the unloading of an LPG vessel, causing a series of large fires in storage tanks).

Although domino accidents are generally thought to cause more severe damage to equipment, this could not be quantified in this analysis due to a lack of specific information in the databases.

9. Domino sequences

The accidents were classified into four different categories: release, fire, explosion and gas cloud. However, one of the limitations of the MHIDAS database is that the "release" category is not available as an incident type for some accidents, though the general information might suggest that a leak has

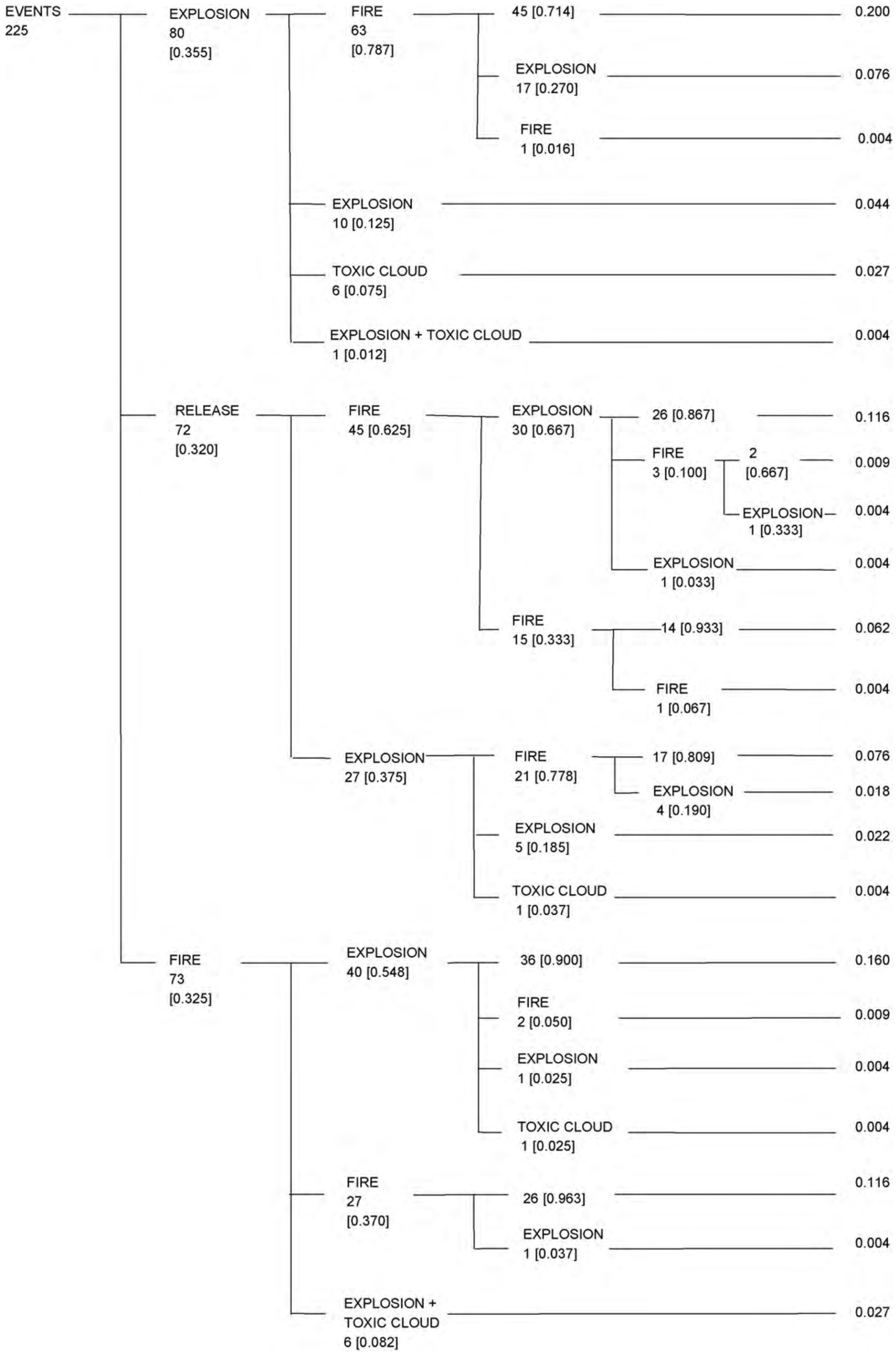

Fig. 5. Relative probability tree showing the diverse domino effect sequences.

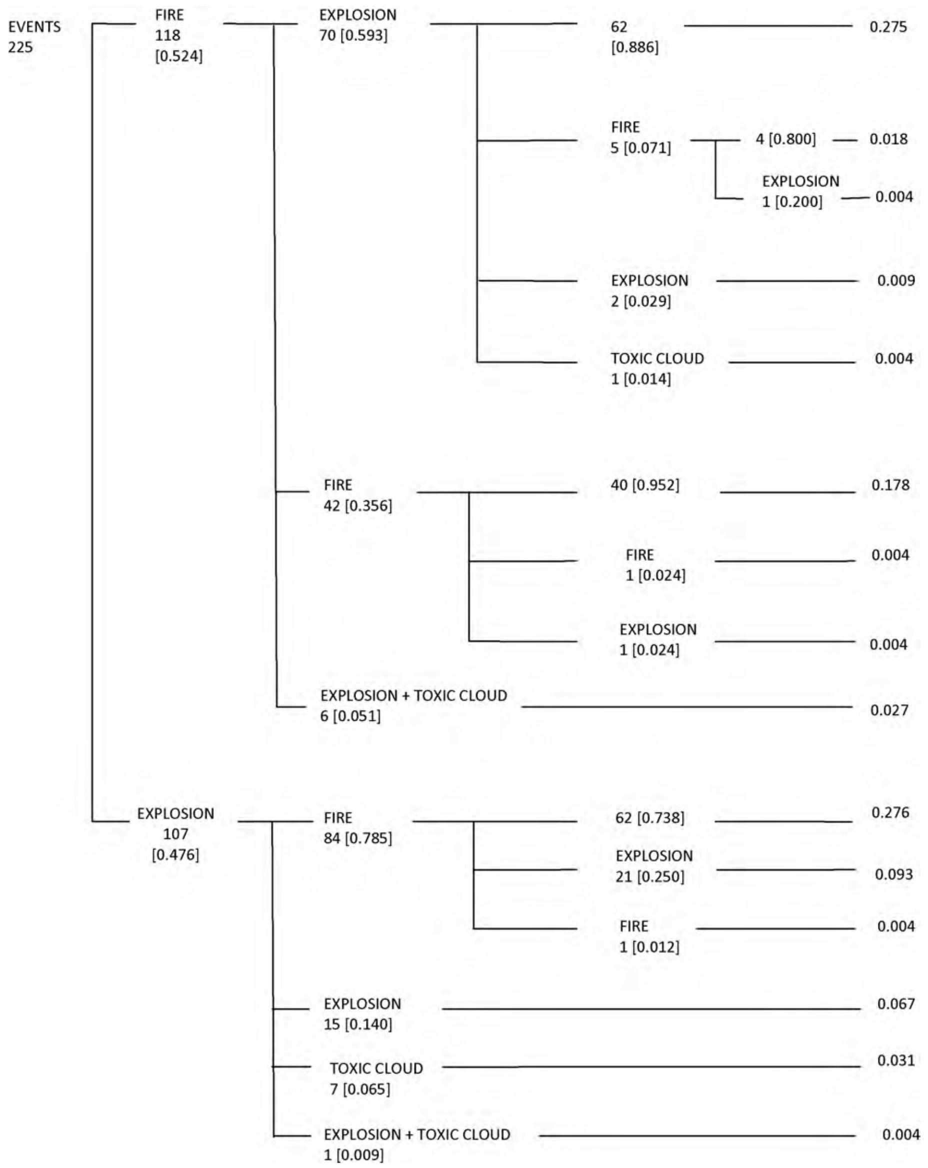

Fig. 6. Relative probability tree showing the diverse domino effect sequences without release as a primary event.

occurred; in fact, most accidents are initiated by a loss of containment.

The sequence of each accident was represented schematically by constructing a relative probability event tree whose branches indicate the different accident scenarios (Figs. 5 and 6). A simple statistical procedure was then used to determine the relative probability of occurrence of each sequence. The number of accidents and the relative probability of occurrence (in square brackets) are shown for each branch; the figures in square brackets represent the probability of occurrence with respect to the level immediately above (i.e. obtained from the ratio of the number of accidents to the number of accidents at the previous level). The values at the end of every branch represent the overall probability of occurrence of the specific accident sequence relative to all possible events.

The relative probability event tree is shown in Fig. 5; this tree includes "release", "explosion" and "fire" as primary events. "Gas cloud" was not considered a primary event because the following considerations were taken into account: if the gas cloud was made of flammable material and ignited, it was considered an explosion; if the flammable cloud was ignited but did not involve any mechanical effects, it was considered a fire; lastly, if it was a toxic gas cloud it would not cause any secondary events.

Of the total number of accidents analyzed, 35.5% started with an explosion, 32% with a release and 32.5% with a fire. Of those that started with a release, 62.5% continued with a fire (followed by an additional explosion in 67% of cases and another fire in 33%) and 37.5% continued with an explosion (followed by a fire in 78% of cases, another explosion in 18% and a toxic cloud in one case).

However, the primary event "release" is loosely defined and is generally overlooked in the databases if it is not followed by another accident. In addition, the description of some accidents suggests that in many cases of "fire" or "explosion" there was probably a previous release that was not recorded in the database. Therefore, it could be considered misleading to include "release" as a primary event.

If "release" is not considered a primary event, the corresponding secondary events become primary events and the tree can be rearranged as shown in Fig. 6. Once "release" has been removed, the primary events are fire (52.4% of cases) and explosion (47.6%). As mentioned above (Fig. 5), "gas cloud" was not considered a primary event for any of the accidents surveyed.

In the accidents that started with a fire, the secondary events were explosion (59% of cases), another fire (36%) and explosion plus a toxic gas cloud (5%). One of the most frequent sequences is an incident which initiates with a fire (for example, a derailment during transportation that leads to a jet fire) that impinges on a tank and causes it to explode. Of the 70 cases in which fire was followed by an explosion, there was no tertiary event in 89% and one tertiary event in 8 cases (11%): fire (5 cases), explosion (2 cases) and toxic cloud (one case). The sequence fire → (explosion + toxic cloud) (6 cases) means that a fire originates one or more explosions and simultaneously causes a toxic cloud due to the decomposition of chemicals (this occurred in warehouses). The sequence fire → explosion → toxic cloud (1 case) indicates that a fire caused an explosion and the explosion released a gas that created a toxic cloud. A fourth-level accident was reported in only one case (with the sequence fire → explosion → fire → explosion).

When fire was the primary event, the secondary accident was another fire in 35.6% of cases (i.e. a fire in other equipment caused by the effects of the initial fire). The primary fire led only to an explosion together with a toxic cloud in 6 cases (5% of the total). Of the accident sequences that started with a fire, 91.5% caused only a secondary accident and 8.5% caused a tertiary accident. A fourth-level accident was reported in only one case.

When the primary event was an explosion (47.6% of the 225 accidents considered), the secondary event was a fire in 78.5% of cases, another explosion or several explosions in 15% (in one case the explosion was associated with a toxic cloud) and a toxic cloud in 7 cases (6.5%). Of the 107 explosions reported as primary accidents and the 71 reported as secondary accidents, at least 40 were BLEVEs associated with a simultaneous fireball, of which 18 involved a tank car derailment.

Of the 225 accidents considered, 193 involved one domino effect (i.e. primary plus secondary accidents), while only 32 involved (at least) two domino effects (a chain of primary plus secondary plus tertiary accidents). This gives a ratio between first-level and second-level domino effect sequences of 6, which indicates that first-level domino accidents are much more frequent than second-level ones. This ratio is much higher than the values reported by Kourniotis et al. [17] and Abdolhamidzadeh et al. [20] (if "release" is considered as a first step (Fig. 5), the ratio would be 1.4, which is much closer to values given by these authors).

Taking the tree in Fig. 6 as the most representative one, the most frequent first-level sequences starting from the primary event (and sometimes followed by a tertiary accident) were explosion → fire (relative probability: 0.37), fire → explosion (relative probability: 0.34) and fire → fire (relative probability: 0.19). The most frequent second-level sequence was explosion → fire → explosion (relative probability: 0.09). Globally, the most frequent final domino sequences (indicated by the values at the end of each branch) were explosion → fire (27.6%), fire → explosion (27.5%) and fire → fire (17.8%).

10. Discussion

Analysis of the domino effect and its importance in accidents involving hazardous materials is a complex task. Accident databases often contain incomplete information, and in some cases it is difficult to determine whether an accident involved a domino effect and, if so, whether it was a first- or second-level domino effect. Given these difficulties, a conservative approach was adopted in this study and only those accidents with clear evidence of a domino effect were considered.

The literature contains few surveys of accidents involving the domino effect, and the term covers a broad conceptual area for which no standard definition has been given. Therefore, clear criteria had to be established to identify those accidents in which a domino effect was definitively observed. The uncertainty associated with the primary event release led to the decision to include this event only when it had further consequences (i.e. toxic cloud).

Analysis of the evolution of accident numbers over time showed a clear increase up to 1980, a period of stabilization during the 1980s and a clear decrease in the period 1990–2007. This trend, recently reported by other authors [25,26], would reflect general improvements to the safety culture of the chemical industry, which include stricter legislation and better training.

The distribution of accident locations is essentially the same as the one obtained in a global analysis of all accidents (i.e. with and without a domino effect): over 80% occurred in developed countries, which seems logical if it is considered that the vast majority of chemical plants are located in these areas. However, this situation could change in the coming years due to the growing trend in the chemical industry for relocation to developing countries.

Flammable substances were the most common substances in domino accidents and were found in 89% of the cases considered. The most frequently found was LPG, followed by oil and gasoline. The generic causes leading to domino accidents were mainly external events and mechanical failure, followed by human error. Impact failure was the most frequent cause in transportation accident scenarios.

Analysis of installation and operation types showed that most domino accidents occurred in storage areas (35%), followed by process plants (28%) and transportation (19%).

In terms of human consequences, the *p*–*N* plot indicates that the lethality of domino accidents is slightly higher than the global average for the chemical industry. When the data were classified by the country, the human consequences of domino accidents were found to be more severe in developing countries. Although a masking effect may be created by the selective collection of information in the databases consulted, the difference in severity clearly reflects the positive impact of regulations and risk-planning policies applied in developed countries.

In terms of damage to equipment, the presence of a domino effect considerably increases the severity of the accident, although the data were insufficient to produce a quantitative assessment of this effect.

The sequences of the different domino accidents (without considering "release" as a primary event) were analyzed by constructing the relative probability event tree. It was found that the primary event was a fire (probability: 0.524) or an explosion (0.476). The ratio between the first-level and the second-level domino effect sequences was 6. The most frequent final domino sequences were explosion → fire (27.6%); fire → explosion (27.5%); and fire → fire (17.8%).

11. Conclusions

Domino effect accidents have been widely studied, but very few historical surveys have been published on them. This survey suggests that the increasing trend traditionally observed in the frequency of major accidents as a function of time has changed over the past 20 years for domino and non-domino accidents. The survey has also shown that domino accidents in underdeveloped countries are more severe than those in countries that are technologically more advanced. This suggests that safety culture measures are working and substantiates the risk-planning policies in developed countries.

Loading/unloading operations caused a significant number of domino accidents. Significant efforts should therefore be devoted to improving safety in such operations, especially in storage facilities where most transfer operations are carried out. A greater effort should also be made to improve the training and education of operators working in industrial plants, as human error has been identified as one of the main causes of accidents.

Most of the substances involved in the accidents were flammable, and the event trees of the accidents analyzed have shown that fires and explosions are the primary domino effect events. Thus, greater emphasis should be placed on adopting safety measures when working with flammable materials.

It is difficult to introduce the domino effect in risk analysis and there are no clear criteria for identifying it. However, relative probability event trees and the frequency of the initiating event can establish the frequency that corresponds to each sequence and offer a systematic means of introducing the domino effect in quantitative risk analysis.

Acknowledgements

The authors thank the Autonomous Government of Catalonia (project No. 2009 SGR 1118 and a doctoral grant for A. P.) and the Spanish Ministerio de Educación y Ciencia (project No. CTQ2008-02923/PPQ) for sponsoring this research.

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