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VAPOUR CLOUD EXPLOSIONS -- AN ANALYSIS BASED ON ACCIDENTS

PART I

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Summary

The accidental release of a combustible gas or liquid may result in an explosive vapour cloud which upon ignition will form a threat to the surrounding area. Models have been developed in order to quantify this effect, but still many questions regarding the accuracy and reliability of such models have to be answered. As research shows the topic to be very complicated, an alternative approach is presented in this paper. This approach is based on the accidents that happened in the past and it is presented in two parts. Part I covers the derivation of trends under which the accidents took place, whereas part II describes a comparison of accidents with a theoretical model.

Introduction

A vapour cloud explosion is a hazard related to the transport, storage, handling and production of combustible gases and liquids [1—3]. The accidental release of any such material into the open may result in a vapour cloud. An ignition of the cloud will cause a flame front that propagates through the explosive part of the cloud. Depending on the velocity of the flame front, a blast wave can be created. This phenomenon is known as a vapour cloud explosion.

For different purposes, like risk analysis studies, safety studies and also design criteria, a reasonable accurate description is required of the consequences for the surroundings of such a vapour cloud explosion. It is therefore necessary to have a calculation model available which enables a realistic quantification of the possible effects. It has been shown, however, that the processes involved are very complicated and up to now it has not been easy to predict the explosion effects in a reliable way for a particular situation.

In order to obtain an improved knowledge of the basics of explosion pro-

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cesses in an explosive vapour cloud a lot of research is carried out, mostly theoretically and on a laboratory scale. This has resulted so far in a better understanding of the important phenomena, but still leaves a lot of questions unanswered. For instance, tests on a laboratory scale will always be small in comparison with real situations and they therefore rely totally on the accuracy and validity of the relevant scaling laws. As those scaling laws are not all known in sufficient detail, inaccuracy is to be expected. As it is also clear that large-scale tests are very expensive and difficult to carry out, it becomes obvious that a thorough look has to be taken at the accidents and incidents that occurred in the past in order to obtain a reliable picture of the large-scale situation. Another advantage of this approach is that data will be obtained which enable a comparison with existing simplified models for vapour cloud explosions. Part II of this paper will deal specifically with this topic.

Here, the accidents will be analysed systematically in order to derive systematic trends and important circumstances which seem to be inherent to a vapour cloud ignition and its consequences.

Limitations of the analysis

In a number of publications and reports a survey of accidents or descriptions of single accidents are presented. Accurate and less accurate descriptions have been obtained of 165 vapour clouds which were ignited. Two criteria have been used in the selection of the relevant accidents; firstly, it had to clear that there was a release of liquid or vapour, and secondly, that ignition took place after the release. Not included in the analysis are therefore vapour clouds that were not ignited or accidents where the ignition took place at almost the same time as the release (e.g., BLEVE). An accident was never rejected because of some lack of information. The appendix presents a listing of all the accidents that were analysed for this study.

An analysis of ignited vapour clouds can be based only on the available information on reported accidents. Two boundaries limit therefore the value of such an analysis, namely the incompleteness of the description of the accidents and the incompleteness of the number of reported accidents.

With respect to the incompleteness of the description, it is to be noted that accident reports are generally not written for the purpose of investigations such as this, which implies that certain data have been omitted intentionally or unintentionally, or have been considered not accurate enough.

Regarding the number of reported accidents, it will be clear that not all accidents can be found in the accessible literature. This will be true especially for releases of relatively small amounts of combustible material or for those cases where little or no damage was caused.

Summarising, it is concluded that the reliability of any analysis of this type and its interpretation is limited by the two boundary conditions mentioned above.

Selected features

For the purpose of this analysis a number of features characteristic of ignited vapour clouds have been selected. The choice was based on the availability of data in accident reports, on the importance for vapour cloud explosion modelling and on aspects directly related to risk analysis and safety studies. Each feature was subdivided into a number of groups in order to permit the derivation of relations between the different groups. The following features have been selected:

Mass

In order to determine whether the amount of material involved is important in relation to the possible consequences of the ignition of a vapour cloud, the mass is a relevant feature. Mass as used in this paper indicates the amount of material released in the accident, which therefore may have contributed to the size of the explosive part of the vapour cloud. The data, expressed in kilogrammes, are divided into 5 groups, namely less than 10^2, 10^2—10^3, 10^3—10^4, 10^4—10^5 and more than 10^5 kg.

Reactivity

It is a well-known fact that different gases react differently under identical circumstances in confined systems [4]. The same division as applied for the confined systems has been used for vapour clouds, i.e., the gases have been divided in three groups of reactivity, namely low, medium and high.

Ignition source

Theoretical studies indicate that the location of the ignition within the explosive region of the vapour cloud is important in relation to the possible effects on the flame front velocity [5]. Two groups have been considered for this study, namely ignition sources which are continuously present (like open fires) and sources not continuously present. The first group will certainly cause a side ignition, whereas the second group might also cause central ignition of the cloud.

Drift

The distance that an explosive cloud can drift into surrounding area is important for risk analysis and safety studies. No distinction was made between "on site" or "off site". This distance is expressed here in metres and divided into three groups: less than 10^2, 10^2—10^3 and more than 10^3.

Explosion

The ignition of a cloud results in a flame front that will propagate through the combustible region of the cloud. Depending on the actual velocity a blast wave will be created. Two groups are identified here, namely those cases where ignition results in an explosion and the cases where ignition results in a flash fire (i.e., no blast wave of any significance is created).

Location
From laboratory tests it is clear that an important reason for flame acceleration is the presence of obstacles and confinement in the explosive mixture [4]. From accident reports it is deduced whether or not obstacles and confinement (e.g., houses, structures) were present at the time of ignition within the cloud.

Delay time
The time lag between the moment of release and the moment of ignition may be an important factor in relation to the development and dispersion of the cloud. This time delay is expressed here in minutes and the categories chosen are less than 1, 1—5, 6—15, 16—30 and more than 30 minutes.

Fatalities
For risk analysis and vulnerability models it is important to know how many fatalities are to be expected as result of an explosion or flash fire. The following groups have been considered: 0, 1—5, 6—15, 16—50 and more than 50.

Wounded
The divisions are as for fatalities.

Domino
It is relevant whether an explosion or flash fire will initiate another release of hazardous material. This is called a domino effect. Three groups have been considered, no domino possible (because there were no vulnerable objects present), domino and no domino effects. In the latter case vulnerable objects were present.

For each accident (see Appendix) involving an ignited cloud, the available information has been analysed in order to determine which category of each feature was relevant. When a certain feature was not given in the reports, it was read as unknown. No effort has been made to derive those features from other known data, as this can only be done on the basis of some prejudged relations. It is, in fact, the purpose of this research, amongst others, to see whether such relations exist. The features are considered to be independent.

Analysis of accident reports
A total number of 165 accidents involving an ignited vapour cloud has been found in the open literature. Those accidents took place in the period 1920—1980 and their distribution of occurrence over this period is presented in Fig. 1. An increase is shown in the number of accidents through those years, which is probably related in some way to the growth of the market for combustible gases and liquids. In the period 1970—1975 nearly 60 cases have been found, which implies an average of nearly one accident a month.

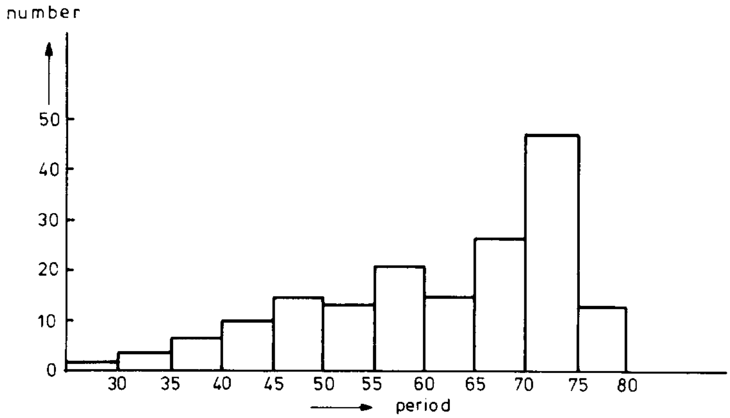

Fig. 1. Number of reported ignited vapour clouds in five-year periods.

A statistical analysis of these accidents [7], based on a complete set of accidents for spill sizes larger than 22 tonnes, indicated that the total number of incidents is about 8000 for the period investigated. These incidents comprise a large number of minor releases.

The available reports, documents and descriptions have been analysed with the aid of the chosen features in order to categorize each accident in as detailed a way as possible. The result of this analysis is presented in Fig. 2 and is discussed below. It should be noted that the percentages given refer to the total number of cases in which the characteristic was known, as displayed in Fig. 2. This is in contrast to the percentages given in Table A2, which include the unknown cases.

Mass

In nearly half of the cases the amount of material involved in the spill was mentioned in the reports. The distribution of the known quantities presented shows a decreasing frequency of occurrence towards lower quantities of material. This will certainly have to do with the incompleteness of the number of reported accidents. A likely reason for this is that the extent of damage is often a criterion for an accident to be reported and that the extent of the possible damage decreases with a decreasing amount of material involved. This suggests also that there is a minimum amount of material below which no significant damage will occur. Another basis for the existence of minimum amount of release can be found using the methods of calculation of effect for those kinds of releases [6]. The data in Fig. 2 suggest that such a minimum spill would be of the order of 100 kg.

Reactivity

Most of the gases and liquids belong to the medium reactivity group.

Ignition source

In only about one-third of the accidents has the possible ignition source

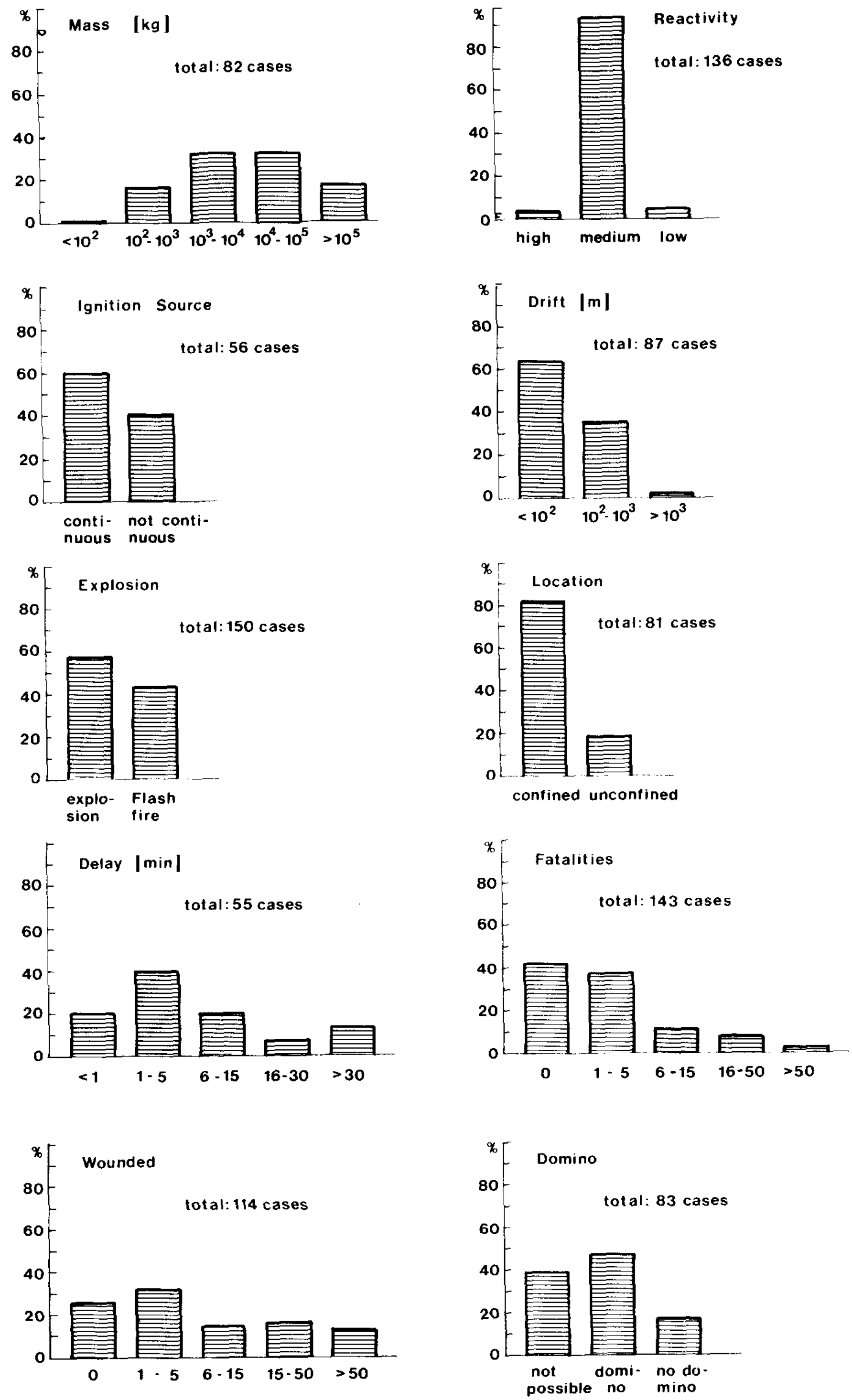

Fig. 2. Relative percentages of occurrences of the selected features for the totals shown.

been identified. In 60% of those cases the source was continuously present and therefore caused side ignition, whereas in 40% an ignition within the explosive cloud may have occurred.

Drift
More than 60% of the vapour clouds were ignited within 100 metres from the location of the spill. In only 2% of the cases did the cloud drift more than 1 kilometre before ignition took place.

Explosion
One of the most important aspects is whether an explosion resulted from the ignition. Regardless of the surroundings, in nearly 60% an explosion was the consequence of the ignition and in slightly over 40% no significant pressure was generated.

Location
In roughly 80% of the cases the vapour cloud was in a semi-confined situation when the ignition took place.

Delay
In about 60% of the cases ignition followed within 5 minutes after the release. Only 12% of the vapour clouds were ignited after a delay of more than half an hour.

Fatalities
A fairly complete record could be obtained of the number of fatalities. It is shown that in about 40% of the accidents there were no fatalities and in only a very few cases there were more than 50 fatalities.

Wounded
As expected, the number of wounded people is higher than the number of fatalities. In 30% of the accidents there were no people wounded and in 13% more than 50 persons were wounded.

Domino
In 40% of the known cases there were no domino effects possible due to the absence of vulnerable objects. But in the remaining 60% the domino effects were likely to happen.

The given percentages of occurrence of the selected features present a first and rough impression of the relative importance of each feature. This compilation also offers the possibility to combine different features and to see whether certain combinations are more likely to happen than others. The next paragraph will deal with this topic.

Relevant aspects of vapour clouds

It has already been mentioned that perhaps the most important aspect of the combustible vapour cloud phenomenon is the answer to the question: "What will happen after a combustible vapour cloud has been ignited?" Generally speaking, there are two possibilities, namely a damaging pressure wave will, or will not, be generated. The first possibility is known as an explosion and the second as a flash fire. In order to deal more specifically with this question the compilation has been divided into one group of cases involving only explosions and in another group containing only flash fires. Furthermore, both groups have been limited to releases of materials of medium reactivity only, in order to minimize differences related to material reactivity. This selected group of materials will react similarly under similar circumstances. The result of this division into two groups is shown in Table 1.

This table shows that for a certain spill range the amount of material involved in the spill has no significant influence on the creation of pressure waves upon ignition. The lower limit of this range will probably be between 100 and 1000 kg, as for smaller amounts the incomplete reporting of accidents is likely to suppress the number of flash fires. Only for amounts larger than 100 tonnes does a flash fire seem to occur more often than an explosion. Based on these figures the preliminary conclusion may be drawn that for the given spill range the amount spilled does not influence significantly the flame propagation process. This, in fact, opens the possibility of scaling laws, based on the mass involved.

A total of 115 cases were categorised as involving materials of medium reactivity, of which 62 could be categorized as explosions and 53 as flash fires. This suggests that the probability that an explosion will occur after ignition of a combustible vapour cloud is about 0.6, and therefore a value of 0.4 would apply for a flash fire for medium reactive materials.

The distance that the front edge of the cloud has travelled does well seem to be a significant value in relation to the explosion—flash fire problem. This is certainly not the case for the location, which, in fact, seems to be very dominant. An unconfined situation was defined, for the purpose of this analysis, as one in which no walls, houses, structures and so on were present in the vapour cloud at the time of ignition. All other situations have been considered as confined. The conclusion may be drawn that when no sizable objects were present in the cloud no explosions have been recorded, and that, in fact, the presence of obstacles and confinement is a necessary condition for an explosion to occur. It can also be deduced from Table 1 that the presence of obstacles and confinement is not the only condition required for an explosion to occur; in many incidents only a flash fire resulted.

The data involving the delay time show that an ignition within about one minute after the beginning of the release will enhance the possibility of an explosion. This will certainly be due to the increased level of turbulence that accompanies many releases. Turbulence is known to enhance flame speeds and consequently the overpressure level in the generated pressure wave. It is also

TABLE 1

Numbers and relative percentages of occurrences of important features with respect to vapour cloud explosions and flash fires for medium-reactive materials

		Explosion	Flash fire
Total		62	53
Mass	$<10^2$ kg	0 (3%)	1 (4%)
	10^2—10^3 kg	6 (14%)	3 (12%)
	10^3—10^4 kg	15 (43%)	10 (38%)
	10^4—10^5 kg	12 (31%)	7 (27%)
	$>10^5$ kg	3 (9%)	5 (19%)
Ignition	continuous	13 (65%)	12 (55%)
	not continuous	7 (35%)	10 (45%)
Drift	$<10^2$ m	16 (55%)	19 (61%)
	10^2—10^3 m	12 (41%)	11 (35%)
	$>10^3$ m	1 (4%)	1 (4%)
Location	semi-confined	37 (100%)	15 (65%)
	unconfined	0 (0%)	8 (35%)
Delay	<1 min	5 (25%)	3 (14%)
	1—5 min	7 (37%)	10 (48%)
	6—15 min	5 (25%)	3 (14%)
	16—30 min	3 (16%)	0 (0%)
	>30 min	0 (0%)	5 (24%)
Fatalities	0	21 (39%)	24 (50%)
	1—5	19 (35%)	17 (36%)
	6—15	8 (15%)	5 (10%)
	16—50	5 (9%)	2 (4%)
	>50	1 (2%)	0 (0%)
Wounded	0	7 (15%)	15 (44%)
	1—5	10 (22%)	12 (35%)
	6—15	9 (20%)	3 (9%)
	16—50	11 (24%)	3 (9%)
	>50	9 (20%)	1 (3%)

Note: the sum per feature is not equal to the total because for a number of incidents the feature could not be determined

worth noting that for delay times larger than half an hour no explosions were found in the literature but only flash fires.

A variable which plays an important role in safety and risk analysis studies, as far as the results are concerned, is the number of fatalities that is to be expected from an unwanted release. From accident records it is shown that in nearly 40% of the explosions there were no fatalities. It should be kept in mind that generally it is not clear whether persons were present at the time of the explosion. For flash fires this percentage related to no fatalities is slightly higher, namely 50%. The discrepancy between explosions and flash fires increases with the higher number of fatalities.

To elaborate this point, the real situation should be considered. At the moment of ignition the vapour cloud covers a certain area. After ignition this area is exposed to intense thermal radiation for a relatively short time. The possible number of fatalities due to the thermal radiation, the possible lack of oxygen and the toxic reaction products is determined by the number of people in the combustible cloud and it is then not relevant if a pressure wave is created. That is to say, for estimating the number of fatalities within the vapour cloud it is not of prime importance whether an explosion or a flash fire occurs. Outside the vapour cloud the situation will be different. As can be seen from many accident reports the area outside the cloud exposed to an intense thermal radiation is very small so that in case of a flash fire no fatalities due to thermal radiation are to be expected outside the burnt area.

Another important factor that can be deduced from accident reports is that outside the vapour cloud no fatalities have ever been recorded which were solely due to primary blast effects. This of course implies that a maximum value can be attached to the overpressure level generated in an accidental vapour cloud explosion. In part II of this paper this will be elaborated further. Fatalities outside a vapour cloud are, in case of an explosion, only due to secondary blast effects, which means that the pressure wave generated causes damage to houses and structures which in turn may cause fatalities. The difference therefore between flash fires and explosions, as far as the number of fatalities is concerned, is determined principally by the secondary blast effects. It is therefore not surprising that a similar trend as found for the fatalities is found for the number of wounded people. The available set of data has also been used to determine a general figure that relates the number of fatalities to the number of wounded people per accident. It turns out that for flash fires the number of wounded is roughly of the same order of magnitude as the number of fatalities, whereas for explosions the number of wounded people is generally an order of magnitude larger than the number of fatalities.

Conclusion

In order to obtain information which is relevant for the study of the consequences of an ignition of an accidentally released vapour cloud, a survey has been made of available accident records. The goal has been two-fold, firstly the derivation of trends which appear to be important for the research in this complicated field, and secondly the comparison of accidents with an existing model. Here, in part I of the paper, is only the first topic covered.

It has been shown that there are two boundary conditions which limit the value of such an analysis based on available records. Those are the incompleteness of the number of accidents reported and the incomplete description of an accident. Taking into account these boundary conditions, the following conclusions have been drawn, based on the information analysed:

(1) In 87 out of 165 incidents the distance within which ignition occurred was known. More than 60% of these 87 vapour clouds were ignited within 100 metres from the location of the spill. In only 2% of these cases did the vapour cloud drift more than 1 kilometre before ignition took place.

(2) In 150 out of 165 incidents it was known whether an explosion or a flash fire occurred. In nearly 60% of these cases the ignition resulted in an explosion; in the other cases a flash fire occurred.

(3) In 143 out of 165 incidents the number of fatalities was known. In about 40% of these cases there were no fatalities and in 25% no one was hurt.

(4) The amount spilled did not influence the probability of an explosion for the investigated accidents in the spill range 1 to 100 tonnes.

(5) Explosions occurred only in semi-confined situations and never in unconfined situations.

(6) A short delay time to ignition enhanced the possibility of an explosion.

(7) For delay-times-to-ignition larger than half an hour only flash fires occurred.

(8) Outside the combustible cloud no one was killed due to primary blast effects.

(9) For flash fires the number of wounded people was of the same order as the number of fatalities. For explosions the number of wounded people was one order of magnitude larger than the number of fatalities.

Appendix

Detailed description of the accidents investigated

The available descriptions of accidents have been analysed in order to determine their characteristic features. Each of the 10 selected features was subdivided into a number of groups, as follows:

Mass (M): amount released in kilogrammes
1. unknown
2. $<10^2$ kg
3. 10^2—10^3 kg
4. 10^3—10^4 kg
5. 10^4—10^5 kg
6. $>10^5$ kg

Reactivity (R): type of combustible gas
1. unknown
2. high reactive
3. medium reactive
4. low reactive

Ignition (I): type of ignition source
1. unknown
2. continuous ignition source
3. not a continuous ignition source

Drift (D): distance that the edge of the cloud has drifted in metres
1. unknown
2. $<10^2$
3. 10^2—10^3
4. $>10^3$

Explosion (E): ignition resulted in flash fire or explosion
1. unknown
2. explosion
3. flash fire

Location (L): presence of obstacles, semi-confinement at time of ignition
1. unknown
2. obstacles, semi-confinement present
3. obstacles, semi-confinement absent

Delay (Dy): time delay between release and ignition in minutes
1. unknown
2. <1
3. 1—5
4. 6—15
5. 16—30
6. >30

Fatalities (F): number of fatalities
1. unknown
2. 0
3. 1—5
4. 6—15
5. 16—50
6. >50

Wounded (W): number of people wounded
1. unknown
2. 0
3. 1—5
4. 6—15
5. 16—50
6. >50

Domino (Do): releases of combustible gas/liquid from damaged objects
1. unknown
2. no domino possible, because of absence of vulnerable objects
3. domino
4. no domino although vulnerable objects were present

All 165 reported accidents have been analysed using this format, the results of which are presented in Table A1. This compilation is summarised in Table A2.

TABLE A1

Analysis of reported accidents

	Date	Place		M	R	I	D	E	L	Dy	F	W	Do
1	1921-08-23	Hull	UK	4	2	1	2	2	3	2	3	1	2
2	1932-12-17	Detroit	USA	1	3	3	2	3	1	1	1	1	4
3	1934-06-02	Huntingdon Beach	USA	4	3	1	1	3	1	3	1	1	3
4	1934-08-29	Campana	Argentine	1	3	1	1	2	1	1	6	1	3
5	1936-10-22	Crowley	USA	4	3	2	2	3	2	3	3	1	2
6	1938-07-05	George West	USA	1	3	2	2	2	2	1	3	5	2
7	1938-05-02	Detroit	USA	1	3	2	2	1	1	1	2	2	1
8	1939-01-02	Newark	USA	1	3	2	1	2	2	1	3	2	2
9	1939-01-30	de Graff	USA	1	3	2	1	2	1	1	3	3	2
10	1939-06-13	Brewster	USA	1	3	2	2	1	1	1	3	2	1
11	1941-06-11	Los Angeles	USA	4	3	2	2	3	3	1	1	1	2
12	1941-10-16	Covington	USA	1	3	3	2	1	1	1	1	1	1
13	1943-01-18	Los Angeles County	USA	4	3	3	3	3	3	1	3	1	2
14	1943	Ludwigshafen?	FRG	5	3	1	2	2	2	2	1	1	1
15	1944-11-15	Cleveland	USA	6	4	1	3	2	2	1	6	6	3
16	1944-11-21	Denison	USA	4	3	2	3	3	1	3	4	1	2
17	1945-11-04	Bayonne	USA	1	1	3	2	3	1	1	1	1	1
18	1945-04-25	Los Angeles	USA	1	3	2	2	1	1	1	2	2	1
19	1945-10-11	Laredo	USA	1	3	1	2	1	1	1	1	1	4
20	1946-08-07	Shreveport	USA	1	3	1	2	2	2	2	2	2	2
21	1946-07-18	Big Bear Lake	USA	1	3	2	2	2	2	1	2	3	3
22	1946-11-19	Greenville	USA	1	3	1	1	2	2	5	3	6	2
23	1947-09-29	Spencer	USA	1	3	1	2	2	2	1	1	1	3
24	1948-10-18	Texas City	USA	1	3	1	3	3	3	1	4	4	1
25	1948-07-28	Ludwigshafen	FRG	5	1	1	1	2	2	2	6	6	1
26	1948-10-13	Sacramento	USA	1	3	1	1	3	1	1	3	2	2
27	1949-11-27	Winthrop	USA	1	3	1	1	3	1	1	2	2	1
28	1949-08-10	Palmer	USA	1	3	1	2	3	2	3	2	3	3
29	1949-06-23	Perth	USA	6	1	1	1	3	1	1	1	1	1
30	1949-07-20	Woodbridge	USA	1	3	2	2	3	1	1	1	2	2
31	1950-10-07	Woodbury	USA	1	3	1	1	2	1	1	1	1	1
32	1950-08-23	Wray	USA	4	3	1	2	3	1	1	3	3	2
33	1950-05-25	Chicago	USA	4	3	1	2	3	2	2	5	1	2
34	1951-03-06	Kubota	USA	5	3	2	2	3	2	4	2	3	3
35	1951-07-07	Port Newark	USA	1	3	1	1	3	2	1	2	4	3
36	1952-07-21	Bakersfield	USA	1	3	3	3	3	2	1	2	2	4
37	1952-01-02	?		1	3	1	1	3	1	1	2	1	1
38	1952-07-24	Kansas City	USA	1	3	2	1	2	2	1	2	3	1
39	1952-01-05	Nashville	USA	3	3	1	2	1	2	1	2	2	1
40	1954	West Virginia	USA	5	1	1	1	2	1	1	2	2	1
41	1954	Tennessee	USA	1	1	1	1	3	1	1	1	1	3
42	1954-10-18	Portland	USA	4	3	2	2	2	2	1	1	1	3
43	1954-04-10	Frederiksburg	USA	1	3	2	2	1	1	1	1	1	1
44	1955-07-22	Wilmington	USA	1	3	1	1	2	1	1	2	2	3
45	1955-10-14	Elkhart	USA	1	3	1	1	3	1	1	3	2	1
46	1955-12-14	Hoopa	USA	1	3	1	2	3	1	1	2	1	1
47	1956	New York	USA	4	3	1	1	2	1	1	2	1	1
48	1956-10-18	Herrin	USA	4	3	1	2	2	2	1	4	1	1

TABLE A1 (*continued*)

	Date	Place		M	R	I	D	E	L	Dy	F	W	Do
49	1956-10-05	Chartage	USA	1	3	3	2	1	1	1	3	3	1
50	1956-03-03	San Jose	USA	1	3	3	2	1	1	1	2	3	1
51	1957-01-08	Montreal East	Canada	1	3	2	3	3	2	1	2	1	3
52	1957-10-24	Sacramento	USA	1	3	1	1	2	2	1	3	3	4
53	1957-09-04	Jackson	USA	1	3	3	1	3	1	1	2	2	4
54	1957-06-23	Sylvania	USA	1	3	1	2	2	2	1	1	1	4
55	1958-05-22	Signal Hill	USA	6	1	1	3	3	2	4	3	2	3
56	1958-02-15	Alma	USA	5	3	3	3	3	2	1	3	3	1
57	1958-04-15	Ardmore	USA	1	3	2	1	2	2	1	2	1	3
58	1958-01-03	Celle	FRG	1	3	1	1	2	2	1	2	1	3
59	1958-07-13	Boron	USA	3	3	1	1	3	1	1	2	1	3
60	1958-07-30	Augusta	USA	1	3	1	1	2	1	1	2	5	4
61	1959-06-28	Meldrim	USA	5	3	2	2	2	2	1	5	1	4
62	1959-05-28	Mc Kittrict	USA	1	3	3	2	3	1	3	2	3	3
63	1959-07-14	Max Meadows	USA	1	3	3	2	1	1	1	1	1	1
64	1960-07-15	Fort Devers	USA	1	3	1	2	1	2	1	1	1	1
65	1960-12-21	Los Angeles	USA	1	3	3	2	1	1	1	1	1	1
66	1960-10-07	Emmerich	FRG	6	3	1	3	2	2	4	3	5	3
67	1961-12-17	Freeport	USA	4	3	1	1	2	2	3	3	2	1
68	1962-07-26	New Berlin	USA	5	3	1	3	2	2	3	4	5	2
69	1962-04-17	Doe Run	USA	5	2	1	1	2	2	3	3	4	3
70	1962-08-04	Ras Tanura	Saudi Arabia	4	3	1	1	2	1	1	3	6	1
71	1962-04	Mariëtta	USA	1	1	2	1	2	2	1	3	3	3
72	1963	Plaquemine	USA	3	1	1	1	2	2	2	2	1	3
73	1963-07-31	Memphis	USA	1	3	1	2	1	1	1	3	3	1
74	1964-01-09	Jackass Flats	USA	3	2	2	2	2	3	1	2	2	2
75	1964	Texas	USA	3	3	1	1	2	2	1	3	5	2
76	1965-07-13	Lake Charles	USA	1	3	2	1	2	1	1	2	4	1
77	1965	Texas	USA	1	3	1	1	2	1	1	1	1	1
78	1965-03-02	Texas	USA	1	3	2	2	3	1	1	2	2	1
79	1965	Baton Rouge	USA	5	4	1	1	2	1	1	2	1	1
80	1965-03-04	Natchitoches	USA	1	1	1	3	1	3	3	5	1	2
81	1966-01	?	FRG	1	3	1	2	2	2	1	2	1	1
82	1966-05-23	Pennsylvania	USA	1	3	2	2	3	2	1	2	2	3
83	1966-01-04	Feyzin	France	6	3	1	1	3	2	6	5	1	3
84	1966	Louisiana	USA	3	3	1	2	2	1	1	3	3	1
85	1966-01-16	Raunheim	FRG	3	4	2	2	2	2	1	2	6	1
86	1966-06-16	New York harbour	USA	6	1	1	3	2	2	3	5	1	2
87	1967-08-08	Lake Charles	USA	4	3	1	3	2	2	4	4	4	1
88	1967-08-21	Martelange	Belgium	5	3	1	2	2	2	3	5	5	4
89	1968-01-20	Pernis	Holland	5	1	1	3	2	2	4	3	6	3
90	1968	Texas	USA	1	1	2	2	3	1	1	3	3	1
91	1968	Louisiana	USA	1	3	2	2	3	1	1	2	2	1
92	1968-12-05	Yutan	USA	1	3	1	2	3	1	6	3	1	1
93	1968-09-24	Port Arthur	USA	6	3	1	3	3	2	3	3	2	3
94	1969-09-09	Houston	USA	1	4	1	2	2	2	4	2	4	2
95	1969-09-11	Black Bayou Junction	USA	1	3	1	1	3	2	6	2	1	3
96	1969-12-28	Fawley	UK	5	1	1	2	2	1	2	1	1	1
97	1969-05-14	Wilton	UK	4	3	3	2	3	1	1	3	5	1
98	1969	Escombreras	Spain	1	1	1	1	2	1	1	3	3	1

TABLE A1 (*continued*)

	Date	Place		M	R	I	D	E	L	Dy	F	W	Do
99	1969-01-25	Laurel	USA	1	3	1	2	2	2	2	3	6	3
100	1970-06-21	Crescent City	USA	1	3	1	2	3	2	2	2	6	3
101	1970-10-23	Hull	UK	1	3	2	1	3	3	1	2	5	2
102	1970-12-09	Port Hudson	USA	5	3	3	3	2	2	5	2	4	2
103	1970	New Jersey	USA	6	1	1	1	2	1	1	2	3	1
104	1970-02-06	Ludwigshafen	FRG	6	3	1	1	2	2	1	4	3	3
105	1970-09-19	Eschenfelden	FRG	6	1	1	1	3	3	6	2	3	2
106	1970-11-12	Hudon	USA	1	3	1	1	3	1	1	4	1	1
107	1971-02-25	Longview	USA	4	3	3	1	2	1	1	3	4	3
108	1971-09	Texas	USA	4	3	1	3	2	1	4	3	4	1
109	1970-11-09	Louisiana	USA	4	3	1	1	2	1	1	2	4	1
110	1971-01-09	Houston	USA	5	3	1	2	3	2	2	3	5	3
111	1971-09-02	Platteville	USA	3	3	3	1	2	1	1	2	3	1
112	1971-08-03	Plattekil	USA	3	3	1	1	2	1	1	2	2	1
113	1971-11-17	Gillette	USA	4	3	1	1	3	1	1	2	3	1
114	1971-12-17	Horseheads	USA	2	3	1	1	3	1	1	2	2	1
115	1972-01-22	East St. Louis	USA	5	3	1	3	2	2	3	2	6	3
116	1972-03-09	Lynchburg	USA	4	3	1	3	3	3	3	3	3	2
117	1972-05-14	Hearne	USA	5	1	1	3	3	2	6	3	3	1
118	1972	Montana	USA	1	3	2	2	3	1	1	3	3	1
119	1972-03-03	?	Brasil	1	3	1	1	2	1	1	5	6	1
120	1972-02-09	Tewksbury	USA	5	3	1	1	3	1	1	3	5	1
121	1972-06-02	Merdenhall	USA	5	3	1	1	3	1	1	2	3	1
122	1972-07-14	Mt. Kisco	USA	3	3	1	1	3	1	1	2	3	1
123	1972-10-10	Ridgefield	USA	3	3	1	1	3	1	1	2	2	1
124	1973-02-22	Austin	USA	6	3	3	3	3	3	4	4	3	2
125	1973	Köln	FRG	4	3	1	1	2	1	1	1	1	1
126	1973	New York	USA	1	3	1	1	1	1	1	5	1	1
127	1973-10-28	Shinetsu	Japan	4	3	3	3	2	2	4	3	5	1
128	1973	Lodi	USA	1	1	1	1	2	1	1	4	1	1
129	1973-02-02	St. Amand les Eaux	France	4	3	1	1	2	2	1	4	5	2
130	1973-07-07	Tokuyama	Japan	1	3	1	1	2	1	1	3	1	1
131	1973-05-28	Rocky Mount	USA	5	3	1	1	3	1	1	2	3	1
132	1974-06-01	Flixborough	UK	5	3	1	3	2	2	2	5	5	3
133	1974-06-29	Climax	USA	6	3	1	3	2	2	1	2	2	3
134	1974-07-19	Decatur	USA	5	3	1	3	2	2	4	4	6	1
135	1974-09-13	Griffith	USA	6	3	1	3	3	1	6	2	1	1
136	1974-01	Florida	USA	5	3	1	1	2	1	1	2	2	1
137	1974-08-25	Petal	USA	1	3	1	4	2	1	1	2	5	1
138	1974	?	UK	4	3	1	1	2	2	5	2	3	1
139	1974-07-18	Plaquemine	USA	5	3	2	2	3	2	3	2	2	4
140	1974-09-21	Houston	USA	5	3	3	3	2	2	3	3	6	3
141	1974	Texas	USA	4	1	1	1	2	1	1	3	4	1
142	1974-04-25	Pitesti	Rumania	1	3	1	1	2	1	1	3	5	1
143	1974-09-05	Barcelona	Spain	5	1	1	1	3	1	3	3	1	1
144	1974	?	Czechoslovakia	1	1	1	1	2	1	1	4	6	1
145	1974-05-21	Meridian	USA	1	1	1	1	3	3	5	3	3	2
146	1975-02-01	Antwerpen	Belgium	4	3	1	1	2	1	3	4	4	1
147	1975-11-07	Beek	Holland	4	3	2	2	2	2	1	4	6	4
148	1975	?	FRG	1	1	1	1	2	1	1	2	3	1

TABLE A1 (*continued*)

	Date	Place		M	R	I	D	E	L	Dy	F	W	Do
149	1975	California	USA	3	2	1	1	2	1	1	2	3	1
150	1975-05-12	Devers	USA	1	3	3	3	3	3	4	3	2	2
151	1975-09-05	Roosendaal	Holland	5	3	2	3	2	2	1	3	4	4
152	1975-04-29	Eagle Pass	USA	5	3	3	2	2	2	2	5	6	2
153	1975-01-17	Lima	USA	1	1	1	1	3	2	3	2	1	4
154	1976	Texas	USA	1	3	1	1	2	1	1	3	4	1
155	1976	Puerto Rico	USA	1	1	2	3	3	1	1	3	3	1
156	1976-02	Texas	USA	1	4	1	1	3	1	1	3	3	1
157	1976-06-16	Los Angeles	USA	1	3	1	1	3	2	3	4	4	2
158	1976	Los Angeles	USA	1	1	1	1	2	1	1	4	5	1
159	1977-12-08	Brindisi	Italy	1	1	1	1	2	2	1	3	5	3
160	1977-12-09	Cartagena	Colombia	1	1	1	1	2	1	1	5	5	1
161	1977-04-03	Umm Said	Qatar	1	1	1	1	2	1	1	4	4	3
162	1977-02-20	Dallas	USA	1	3	1	1	2	1	3	1	1	1
163	1977-06-19	Puebla	Mexico	1	3	3	1	3	1	1	3	2	3
164	1977-07-20	Ruff Creek	USA	6	3	3	4	3	3	6	3	2	2
165	1980-03-26	Enschede	Holland	3	3	2	2	2	2	1	2	3	2

TABLE A2

Summary of data from Table A1

Number of registered accidents		165	
Mass	1. unknown	83	(51%)
	2. <100 kg	1	(<1%)
	3. 10^2—10^3 kg	13	(8%)
	4. 10^3—10^4 kg	27	(16%)
	5. 10^4—10^5 kg	27	(16%)
	6. >10^5 kg	14	(9%)
Reactivity	1. unknown	29	(18%)
	2. high reactive	4	(2%)
	3. medium reactive	127	(76%)
	4. low reactive	5	(2%)
Ignition source	1. unknown	109	(66%)
	2. continuous source	33	(20%)
	3. not continuous source	23	(14%)
Drift	1. unknown	78	(48%)
	2. <10^2 m	55	(33%)
	3. 10^2—10^3 m	30	(18%)
	4. >10^3 m	2	(1%)
Explosion	1. unknown	15	(9%)
	2. explosion	86	(52%)
	3. flash fire	64	(39%)
Location	1. unknown	84	(51%)
	2. semi confined	68	(41%)
	3. unconfined	13	(8%)

Delay	1. unknown	110	(67%)
	2. <1 min	12	(7%)
	3. 1—5 min	21	(13%)
	4. 6—15 min	11	(7%)
	5. 16—30 min	4	(2%)
	6. >30 min	7	(4%)
Fatalities	1. unknown	22	(13%)
	2. 0	60	(36%)
	3. 1—5	52	(32%)
	4. 6—15	17	(10%)
	5. 16—50	11	(7%)
	6. >50	3	(2%)
Wounded	1. unknown	51	(30%)
	2. 0	30	(18%)
	3. 1—5	35	(21%)
	4. 6—15	16	(10%)
	5. 16—50	18	(11%)
	6. >50	15	(9%)
Domino	1. unknown	82	(50%)
	2. not possible	32	(20%)
	3. domino	38	(23%)
	4. possible but no domino	13	(8%)

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