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VAPOUR CLOUD EXPLOSIONS — AN ANALYSIS BASED ON ACCIDENTS

PART II

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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 a lot of questions regarding the accuracy and reliability of such models exist. As research shows the topic to be very complicated, an alternative approach is presented in this paper. The 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

In order to estimate the consequences for the surrounding area of an accidental release of a combustible gas or liquid, several calculation models are needed. Each of those models is supposed to cope with a link in the chain of events that may take place between the moment of release and the moment that damage is caused. One of the links involves the calculation of the effects following the ignition of a combustible vapour cloud. This paper will deal specifically with these vapour cloud explosions.

It is well known that this field is very complicated and that other sources of information that may lead to a better description of the real processes will be valuable. As a lot of information is incorporated in the literature on accidental vapour cloud explosions, our effort has been directed to the analysis of accidents that happened in the past. This analysis is presented into two parts, namely the derivation of trends and the selection of relevant parameters based on known accidents (which was presented in part I of this paper) and the comparison of the real explosion effects with a theoretical model [1]. This

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second topic forms the subject of this article, part II of the paper.

Although the ignition of a combustible vapour cloud results in effects like heat radiation and pressure waves, this paper will be limited to the pressure effects. That is to say, only vapour cloud explosions are considered and not flash fires. The reason for this is, amongst others, that heat radiation is only important in the cloud itself and in a very narrow region around the cloud. Generally speaking, this effect is not important for the determination of damage outside the cloud in case of an explosion.

Discussion

General aspects

The release of a combustible gas or liquid may result in the formation of a combustible vapour cloud. That is to say, a part of this cloud may be within the explosion limits. An ignition of this explosive region in the cloud will lead to the formation of a flame front that propagates through the whole explosive region of the cloud. Whether a pressure wave is generated that may cause damage to the surrounding area depends only on the resulting flame speed. Generally speaking it is the ratio of flame speed and speed of sound which forms the important factor. This can be understood easily by considering the fact that the flame speed determines the rate of the energy release, whereas the speed of sound limits the velocity with which the liberated energy can be transported in the form of pressure waves away into the surrounding area. It will be clear that the higher the flame speed, the higher the overpressure in the pressure wave will become. The velocity of those pressure waves is almost constant (for a given situation) and their velocity can only increase slightly due to the transition of the pressure wave into a shock wave.

This simple and inevitably crude description of the relevant variables shows that the knowledge of the flame speed as a function of time is a very important variable to know a priori for a given situation. This flame-front velocity can easily vary by several orders of magnitude. In a quiescent mixture the flame speed is, for the most relevant hydrocarbons, a few metres per second, which is two orders of magnitude lower than the speed of sound, and therefore no significant pressure wave is to be expected. The flame speed should, in fact, increase by at least a factor ten before a damaging pressure wave is created.

The fact that this flame speed in actual situations can not be predicted on a pure theoretical basis is one of the reasons leading to the approach adopted in this paper. Part I has led to the conclusions that for releases larger than about 1 tonne the mass involved in the cloud (the extent of the explosive region) is not an important factor in relation to the possibility of an explosion, and that, most significantly, the presence of houses, structures, walls and so on, is a necessary condition for the generation of an explosion. In other words, the presence of obstacles forms a necessary condition for the creation of flame acceleration. These conclusions were drawn for materials that are considered to be of medium reactivity. Most of the research directly related to vapour cloud explosions is carried out in this area of interest, namely interaction with obstacles.

It is nevertheless still not possible to give a priori the flame speed for an actual situation. The approach in the past to this problem was to assume a flame speed and to calculate the related pressure wave. The purpose of this paper is to determine from the extent of the damage the characteristics of the pressure wave, and to see whether this method can provide maximum or minimum levels for the pressure waves. These levels will act as an indication of the flame speed during an explosion. It should be noted that the flame speeds are not constant but vary with time. It will therefore never be possible to give the actual flame speed as a function of time on the basis of maximum overpressures. It is possible that several different combinations may lead to roughly the same result.

Vapour cloud explosion modelling

With regard to the problem of vapour cloud explosion modelling as discussed in the previous paragraph, it is not surprising that a calculation model for another type of explosion was used in the past for estimating the effect of a vapour cloud explosion. The most frequently used method was the model based on detonations of solid explosives like TNT and Pentolite. Overpressure, impulse and positive phase duration are known for this type of explosion, sometimes directly as a function of potential damage with distance.

By using this type of explosion as an equivalent of a vapour cloud explosion the problem of the estimation of the expected flame speed is avoided. Another problem is then of course introduced, namely the translation of the available combustion energy in the cloud into an amount of solid explosives. In fact it is the same problem but the question posed is a different one.

The availability of explosion characteristics of TNT has led to the use of these data in predictions and accident analyses. The link between the two different types of explosions is usually made through the definition of a yield factor. This yield factor is defined as the quotient of the amount of explosion energy of a certain mass of TNT and the amount of combustion energy in the cloud, usually expressed as a percentage. In this definition of yield use is made of the explosion energy of TNT because only a part of the combustion energy of TNT is transferred into a blast wave. This explosion energy of TNT is 4×10^7 J/kg.

Similarly, it is also true that only a percentage of the combustion energy present in the cloud is available as blast wave energy. Calculations have shown that this percentage is about 20% for detonations. This percentage is expected to be lower for deflagrations, because of lower reaction rates and higher losses.

In a number of reports describing accidents the yield is given or calculated (for accidents 1, 25, 67, 69, 74, 75, 79, 85, 87, 89, 102, 103, 109, 115, 127, 132, 134, 138, 141, 149 and 151; see the appendix in part I). It is given either directly as yield or indirectly as an equivalent amount of TNT. When the data of several accidents are compared, a general trend is noted, indicating that the yield increases with an increasing amount of TNT. In more detail: for equivalent amounts of TNT less than 100 kg the yield is between 0.1 and 1%, for equivalent amounts between 100 and 1000 kg the yield is about 1%, whereas above 1000 kg the yield factor is between 1 and 10% (Fig. 1).

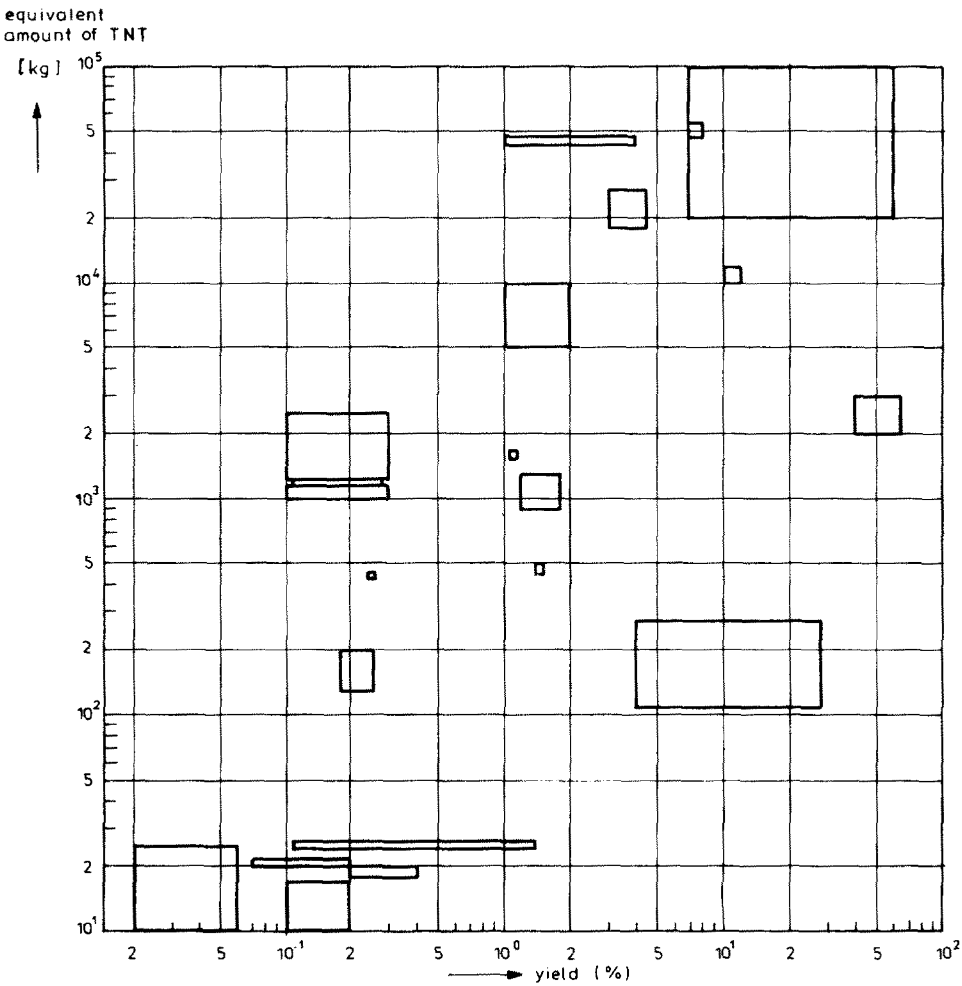

Fig. 1. Yield as a function of the equivalent amount of TNT.

Although it was concluded in part I of this paper that the mass involved in an accidental release has no significant effect on the probability of an explosion, the yield figures indicate an increase in the severity of the explosion (i.e., damage) with an increasing amount of solid explosives. It is well known that the greater the amount of explosive material, the larger the damage distances will be. But the figures produced here suggest that after correction for the mass increase with the appropriate scaling laws there still remains an increase in damage distances with the energy-scaled mass. This point will be elaborated further and explained below.

Another important factor in relation to vapour clouds is of course the estimated amount of material in the cloud at the time of ignition. Very often this value is not calculated or estimated, but instead the spill size is used in the yield definition. As this mass appears in the denominator it will be clear that in cases where the spill size is used, the derived yield value has to be read as a minimum value.

In an earlier publication [1] a model for a vapour cloud explosion was presented assuming certain flame speeds for several combustible gases. This model is given in Fig. 2, showing in the upper half the peak overpressure

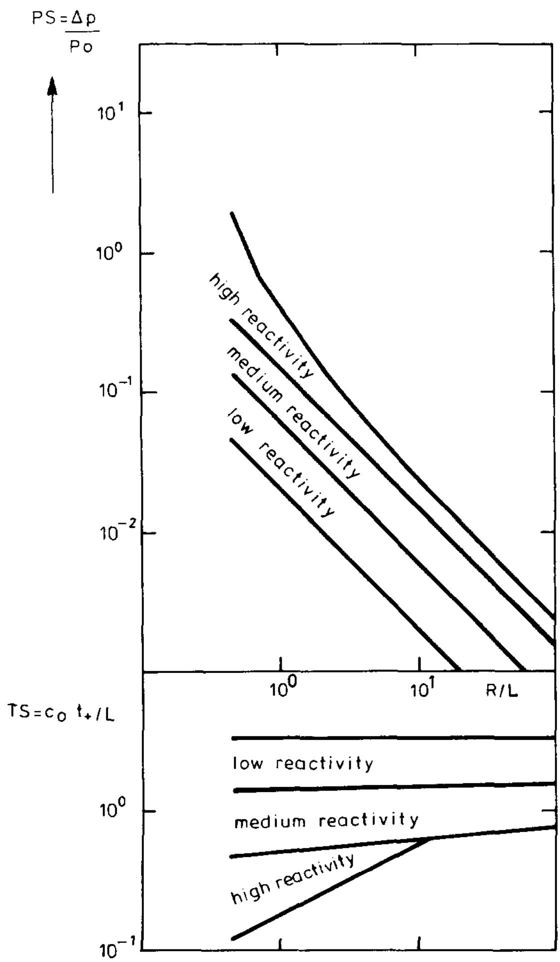

Fig. 2. The vapour cloud explosion model.

versus distance relation and in the lower half the positive phase duration versus distance relation. All variables are presented in a dimensionless form based on Sachs scaling laws. This type of presentation permits the use of one relation for any mass. The combustible gases have been divided into three groups of different reactivity, i.e., low, medium and high. It has already been noted in part I that most known accidents took place with medium-reactive materials.

As stated in the introduction, no attention will be paid to the relation between flamespeed and peak overpressure, but accident reports will be used to estimate the relevant peak overpressures. The reliability of the results produced by the given model can easily be checked on the basis of those conclusions. Firstly, this will be done for general points found in more than one accident and about which no contradicting information exists, and secondly, the data contained in accident reports will be compared directly with this explosion model.

General comparison of accidents with the vapour cloud explosion model

A number of phenomena have been observed in accidents which in principle offer the possibility to derive boundaries for an explosion model for vapour clouds. These phenomena are:

a. Outside the explosive vapour cloud no person has been killed directly by blast effects.
b. Outside the explosive vapour cloud, on a few occasions persons have been knocked down by the blast but no one was seriously injured in those cases.
c. Outside the vapour clouds no car has been overturned by the blast wave.
d. Damage to houses is a real possibility.
e. The observed yield of an explosion increases with increasing equivalent amount of TNT.

Before an analysis of each phenomenon can be presented, the pressure wave characteristics have to be transferred to a form which enables a comparison with damage criteria. Most damage criteria are formulated in so-called *P—I* diagrams, in which *P* stands for peak overpressure and *I* for impulse. As the vapour cloud explosion model gives peak overpressure and positive phase duration only, the impulse has to be approximated. A pessimistic approach is adopted in this case by presenting the overpressure time curve of the shock wave as a triangle. Using the same dimensionless form (Sachs scaling) as used in Fig. 2 it can easily be shown that the impulse is then represented by:

$$I_S = P_S \; T_S/2$$

in which $I_S = I\, c_0 / P_0 \; L$.

The characteristic explosion length, L, as used throughout this paper is defined as follows (Sachs scaling):

$$L = (E/P_0)^{1/3}$$

in which E stands for the available combustion energy in the case of hydrocarbons and for the explosion energy in the case of solid explosives. As consideration has been limited to medium-reactive gas it can be deduced from Fig. 2 that outside the burning cloud the maximum values for P_S and T_S are:

upper bound: $P_S = 0.3$, $T_S = 0.067$
lower bound: $P_S = 0.13$, $T_S = 1.4$.

As the maximum characteristic explosion length, L, found in accidents is about 300 m, it can easily be calculated that the maximum values of peak overpressure, Δp, and impulse, I, are, according to the theoretical model:

$\Delta p = 3 \times 10^4$ Pa and $I = 6 \times 10^3$ Pa s
$\Delta p = 1.3 \times 10^4$ Pa and $I = 8 \times 10^3$ Pa s

This determination of the maximum values enables a comparison to be made with general damage criteria in order to see whether these maximum values are realistic. That is to say that no damage is found in reality which is caused by a blast wave with characteristics higher than the derived maximum values.

Damage criteria in a useful format for this analysis can be found in Ref. [2]. The first topic discussed is that it is noted from accident reports that no person was killed by primary blast effects outside the vapour cloud. In Fig. 3

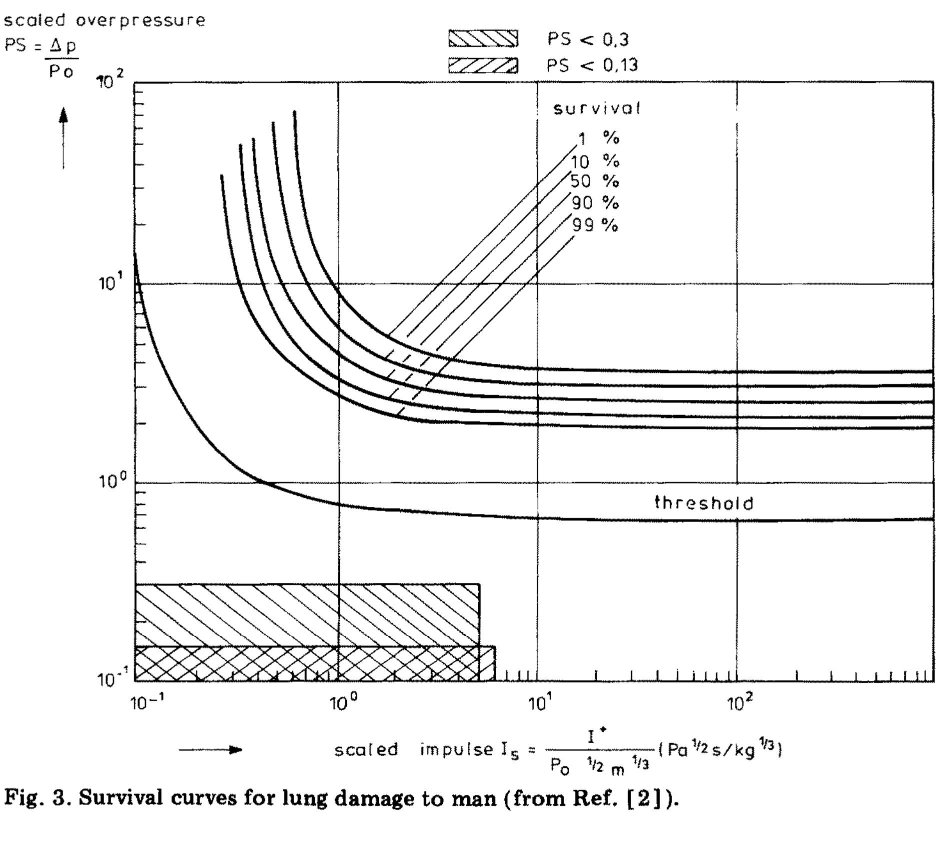

Fig. 3. Survival curves for lung damage to man (from Ref. [2]).

the criteria for lethal lung damage are presented together with the maximum values for a vapour cloud explosion as calculated here. It has been assumed that the weight of a person is 75 kg. It can be seen that there is no contradiction between the predicted values, the damage criteria and the actual observations.

The second observation is that some people have been knocked down by the blast wave but no one was seriously injured or killed. In Figs. 4 and 5 comparisons between damage criteria and the maximum blast characteristics are given. Here no contradiction between the theoretical and real values is found. It should be noted that other combinations of overpressures and impulse could lead to the same result, a lower peak overpressure requiring a higher impulse.

A third observation is that no cars have been overturned by the blast wave from a vapour cloud explosion. Adopting the analysis method as presented in Ref. [2] it is easily shown that the theoretical predicted impulse is about a factor three less than the critical impulse necessary to overturn cars.

The fourth observation is the damage to houses in the neighbourhood of the exploded vapour cloud. The general comparison as given earlier in this paper for other damage criteria is presented in Fig. 6. This can only be interpreted as a general comparison, as there are many types of housing each having their own characteristic damage criteria. But nevertheless, it can be seen

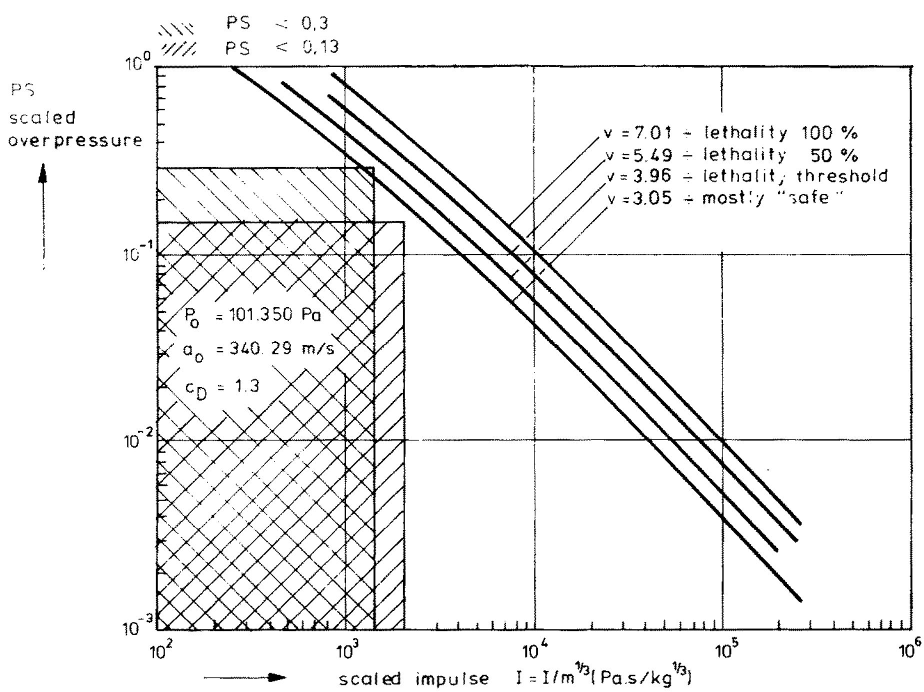

Fig. 4. Skull damage (from Ref. [2]).

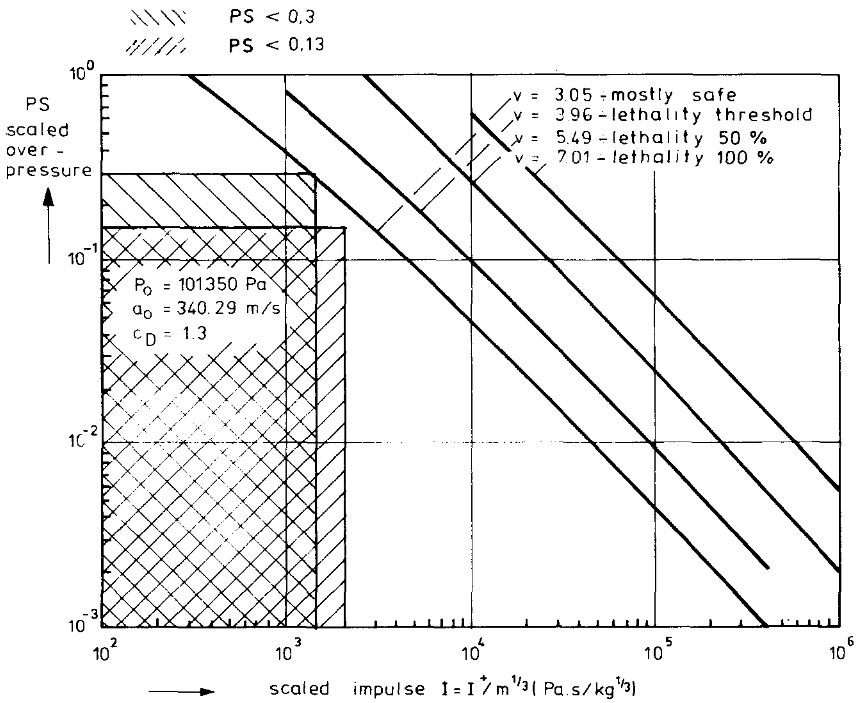

Fig. 5. Lethality from whole body translation (from Ref. [2]).

from this figure that the maximum values for the blast wave are not unrealistic.

A fifth observation comes from the analysis of accident reports. It shows that there is a tendency for increasing yield with increasing equivalent amount of TNT. To express this in other words, with an increasing total amount of explosive, the damage created per unit explosive mass is greater. This can only be true if the blast wave characteristics for a vapour cloud explosion are different from a TNT explosion and to be more precise the impulse and/or positive phase duration for a vapour cloud explosion must be larger than for an (energy-)equivalent TNT explosion at the same peak overpressure. That this is true can be deduced from the fact that the positive phase duration is principally determined by the duration of the explosion process and, as the two types of explosion process differ some orders of magnitude in velocity, the positive phase duration will be larger for vapour cloud explosions and so the general trend found with accidents reports is explained.

In conclusion, the values predicted by the theoretical vapour cloud explosion model are not in contradiction with the practical observations in accidents. Although the conclusion has to be in a qualitative sense, it is seen that the predicted maximum values are not unrealistic.

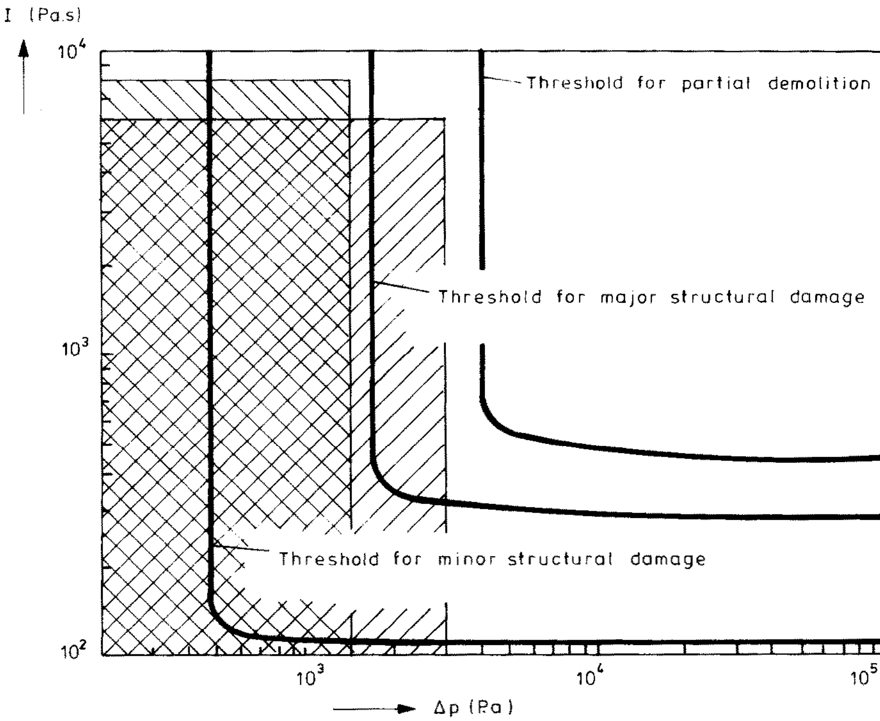

Fig. 6. Pressure versus impulse diagram for building damage (from Ref. [2]).

Comparison of accidents with the predictions of the vapour cloud explosion model

In the previous paragraph conclusions have been drawn from observations at accidents in order to determine on a general basis values for the blast wave characteristics. This paragraph will deal with more specific data per accident. As accidents are never instrumented, the created damage is the only measure for the intensity of the blast wave. In fact, the damage observed can, in the ideal case, be used to identify the blast wave which has struck the object. This demands an analysis per object which is nowadays becoming possible but, nevertheless very extensive. It also requires detailed knowledge of the construction of the object, which is seldom available for objects that have been damaged in the past. It is also a question whether such an analysis is useful with regard to the inaccuracy of the data and calculation methods for determining the extent of the explosive cloud. For the purpose of this work preference is given to simple and general criteria. The criteria are limited to the peak overpessure, Δp, of the created blast wave and are formulated as follows:

$\Delta p = 3 \times 10^4$ Pa: extensive structural damage
$\Delta p = 10^4$ Pa: boundary of structural damage to houses
$\Delta p = 3 \times 10^3$ Pa: extensive window pane damage
$\Delta p = 10^3$ Pa: boundary of window pane damage.

The vapour cloud explosion model used in this comparison is presented in Ref. [1] and relates the peak overpressure to a scaled distance from the explosion centre. The scaling is performed by dividing the distance by a characteristic explosion length. This characteristic explosion length, L, is defined as follows:

$$L = (E/P_0)^{1/3}$$

in which E stands for the total available combustion energy within the cloud and P_0 represents the atmospheric pressure. This presentation has been chosen to be consistent with solid explosives relations and data, and because it is dimensionless in any self-consistent set of units. As can be seen from the formulated general criteria the positive phase duration is disregarded in this comparison.

Using calculation models to estimate the amount in the explosive region [3] the energy involved is determined. This permits the actual distances to be presented in a dimensionless form and so a comparison with the model is realized. For the sake of brevity only the most important and relevant information per accident is presented below in brief format. The following accidents, mentioned in the literature, have been used for a comparison.

(1) *F.R.G., 1943.* A railroad tankcar filled with 16.5 to 19.5 tonnes of butadiene bursted. The resulting cloud was ignited within 10 to 25 seconds and caused damage to the surroundings [4, 5].

A detailed damage analysis is presented in Ref. [5], which, when taken together with accidents 2 and 9, result in a peak overpressure distance relation outside the vapour cloud, represented by dimensionless variables as follows:

$$\frac{\Delta p}{P_0} = 0.2 \times \frac{L}{R}$$

Inside the exploding vapour cloud peak overpressures of 0.3 bar were deduced. For the characteristic pressure levels of 0.1, 0.03 and 0.01 the values of the dimensionless distances are 2, 6, and 20, respectively, based on the derived relation.

(2) *Ludwigshafen, F.R.G., 1948.* A railroad tankcar, containing 30×10^3 kg of dimethyl ether suddenly bursted. The vapour cloud exploded shortly thereafter.

This accident is similar to the accident described under number 1, and so is the overpressure relation [5], expressed in dimensionless units. So, for the characteristic overpressure levels of 0.1, 0.03 and 0.01, the related distances are respectively 2, 6 and 20.

(3) *Portland, U.S.A., 1954.* LPG escaped from a duct and a vapour cloud with a radius of 60 m was formed. The explosion caused damage to storage

tanks located at 60 m [6].

The apparent distances show that the storage tanks were inside or very close to the vapour cloud. In Ref. [6] it is stated that the overpressure was about 0.24 to 0.48 bar.

(4) *Freeport, U.S.A., 1961.* About 23 m^3 of cyclohexane was released as a valve failed. The explosion damaged the roof of a control building [7—9].

At 30 m from the explosion centre the overpressure was estimated to be about 0.14 bar. Considering the amount of cyclohexane involved, the 30 m falls within the explosive cloud.

(5) *Raunheim, F.R.G., 1966.* Liquid methane escaped from a vaporizer and formed an explosive cloud. Although in Ref. [7] only methane is mentioned, Ref. [9] reports a methane—ethane mixture. Extensive glass damage was mentioned up to 400 m, whereas light glass damage was reported up to 1200 m [7, 9].

In Ref. [7] it is stated that about 500 kg of methane was involved in the explosion, which determines the characteristic explosion length to be 63 m. The characteristic pressure levels for the different types of damage were 0.03 and 0.01 and the related dimensionless distances are calculated to be, respectively, 6.5 and 19.

(6) *Pernis, The Netherlands, 1968.* A vapour cloud with about 50 to 100 tonnes of higher hydrocarbons exploded about 13 min after release. The result was a devastated area of about 250 × 350 m^2, and damage to buildings and installations within an area of 1300 acres. Window pane damage and damage to roofs was observed up to 6 km [10, 11].

As the material involved in the cloud was not known, only a general figure can be used for the calculation of the energy involved. With a combustion energy of 4×10^7 J/kg the characteristic explosion length is 270 to 340 m. Using the same procedure as already described, one arrives at dimensionless distances of about 1, 3 and 20 for the overpressure levels of, respectively, 0.3, 0.1 and 0.01.

(7) *Port Hudson, U.S.A., 1970.* An 8 inch pipeline transporting liquid propane suddenly ruptured. After 24 min the vapour cloud exploded [12, 13].

Calculations on the basis of Ref. [3] indicate that under the appropriate weather and terrain conditions about 1000 kg of propane was within the explosion limits at the time of the explosion. This gave a characteristic explosion length of about 165 m. Table 6 of Ref. [12] relates observed damage to amounts of TNT. Transferring to the variables used in this paper results in:

P_S	R/L	P_S	R/L
0.22	1.4	0.07	3.1
0.08	2.8	0.11	3.7
0.08	2.6	0.07	3.3

In Table 7 of Ref. [12] it is stated that the 100% window pane damage boundary ($P_S \cong 0.03$) was at about 1 mile ($R/L = 9.5$). The outer boundary window pane damage boundary is taken to be 2½ miles [13]. This corresponds with an R/L value of 24 with an overpressure, P_S of 0.01.

(8) *East St. Louis, U.S.A., 1972.* A railroad tankcar carrying propylene was punctured. As the tankcar was moving, the release took place over some distance. The vapour cloud exploded after 8 to 10 min [14, 15].

From the accident data it is deduced that the length:width ratio of the cloud was about 10:1, with a total area of 2×10^4 m². It is also mentioned that the cloud was of low height. Interpreting this as an average height of 1 to 5 m, the volume of the cloud was 2×10^4 to 10^5 m³. With an average propylene concentration of 6% (lower explosion limit = 2%, upper explosion limit = 11%), it is seen that about 4 to 18% of the released propylene might have been within the explosion limits. This corresponds to a characteristic explosion length of 100 to 160 m. The damage pattern shows a circular character, but it is remarkable that the circles are not concentric, the centres being shifted in the wind direction [14], although the spill took place in a direction perpendicular to the wind direction. Determining the minimum and maximum values of R/L one arrives on the basis of the damage pattern given in Ref. [14] at the following values: Heavy structural damage ($P_S = 0.1$) occurred for regions with R/L values varying between 1.4 and 4.2. Glass damage P_S = 0.03) varies between R/L equal to 3.3 and 11.0 and light glass damage (P_S = 0.01) took place for an R/L value between 4.6 and 17.

(9) *Flixborough, U.K., 1974.* Through a ruptured pipeline about 50 to 60 $\times$ 10^3 kg of cyclohexane was released. An explosion followed shortly thereafter [5, 16–19].

As shown in Ref. [4], this accident might be compared with the accidents 1 and 2. The overpressure versus distance curves are found to be similar for the three cases. The estimated amount in the explosive region was about 30×10^3 kg of cyclohexane, which determines the characteristic explosion length to be 160 m. It is also interesting to see that in this case the damage patterns are shifted in the wind direction [18].

(10) *Decatur, U.S.A., 1974.* Because a railroad tankcar was punctured, about 69×10^3 kg of butane was released within 8 to 10 min [7, 20].

According to Ref. [20] the release rate was 5000 gallon per minute, which indicates that the release was completed in about 6 min. If the source is considered to be instantaneous, a minimum of 70% of the released butane could be within the explosion limits [3]. In Ref. [20] it is stated that the area covered by the cloud was 800 × 1200 m². Assuming an average butane concentration equal to the lower and upper explosion limit, an average height of 1.50 and 0.28 m, respectively, is deduced. As these are average values based on areas, the derived values are considered to be not unrealistic.

The characteristic explosion length based on these figures is 280 m. The damage data show that within a radius of 750 m houses were structurally damaged. The boundary of this type of damage has been put equal to P_S = 0.1, which corresponds for this accident with an R/L value of 2.7. The window pane damage boundary (area C of Ref. [20]) was found to vary from 1.2 to 4 km, which results in an R/L value of, respectively, 4 and 14.

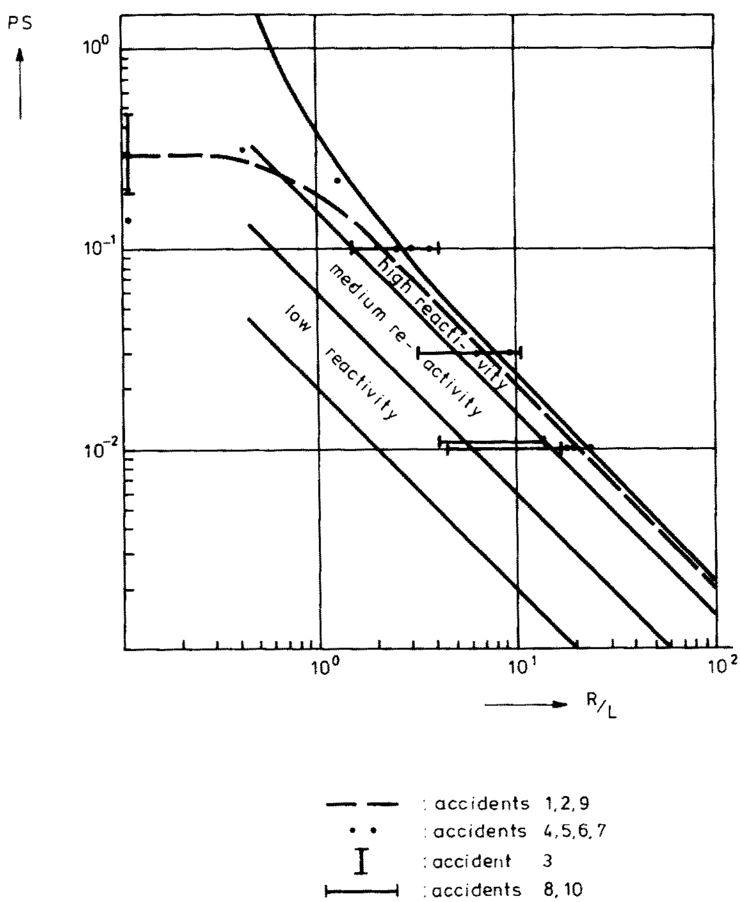

Fig. 7. Comparison of the vapour cloud explosion model with accidental vapour cloud explosions.

On the basis of general damage criteria, 10 vapour cloud explosions have been analysed to enable a comparison with a model for this type of phenomena. This comparison is presented in Fig. 7, in which only data derived in this paragraph are used. It is shown that the effects predicted by the theoretical model are in general agreement with the actual effects of vapour cloud explosions given the assumptions made. This is of course not unexpected, as realistic explosion models are usually checked with well-known accidents.

Besides this conclusion, some other relevant remarks can be made with respect to important aspects of the modelling of vapour cloud explosions. Some of the aspects are cloud shape, location of the ignition source and amount of material involved.

(a) *Cloud shape.* The theoretical explosion model assumes a hemispherical cloud laying on the ground. The vapour clouds that have been described above had in reality different shapes, varying from spherical to flat cylindrical. Although theoretical studies [21, 22] indicate a strong dependence on the shape of the cloud, this is not confirmed by the given comparison. This may lead to the conclusion that the explosion process for a major part of the cloud has a (hemi)spherical character. This should be interpreted in conjunction with an earlier conclusion, i.e., that obstacles are required in the cloud in order to generate a significant flame speed.

(b) *Location of the ignition.* For the accidents described it is seen that ignition has taken place in the middle as well as at the edge of the cloud. The observed damage patterns do not show an indication that the location of the ignition source is important. This seems to be in contradiction with theoretical studies [22]. However, combined with the philosophy mentioned under (a) it gives rise to the conclusion that the major contribution to the explosion process seems to come from that (those) part(s) of the cloud where almost hemispherical flame propagation(s) is (are) possible, and that it is not important how this process is initiated, nor where the ignition took place.

(c) *Amount of material.* In most of the cases described, the amount of explosive material in the cloud is estimated and includes therefore a possible uncertainty. Taking into account that the theoretical model assumes an uniform stoichiometric mixture (which causes a nearly optimum release of available energy) and that the upper bound of the high reactivity region stands for a detonation it is seen that a very large part of the cloud contributes to the blast wave. It should also be kept in mind that if the amount in the explosive region is supposed to be an overestimation, the real values will shift towards higher dimensionless distances, since the cloud volume appears in the denominator.

Conclusion

An analysis has been presented of the effects of some vapour cloud explosions in comparison with a theoretical explosion model [1]. It has been shown that on the basis of damage criteria the model presents generally realistic values for the effects. A more specific comparison is also presented for a number of given accidents which shows similar findings.

The main conclusions that have been drawn from the analysis as presented in parts I and II of this paper lead to the following description of the important variables with respect to combustible vapour clouds:

(a) It is a necessary condition that obstacles or other forms of semi-confinement are present within the explosive region at the moment of ignition in order to generate an explosion. However, under those conditions a flash fire is still a real possibility. In the absence of obstacles of other forms of semi-confinement no explosion has ever been recorded in accidents but only flash fires have occured.

(b) The actual shape of the vapour cloud with respect to the explosion modelling does not seem to be an important factor.

(c) The location of the ignition source does not in general influence the damage pattern observed after the explosion.

These conclusions give rise to the following description of a vapour cloud explosion.

After the release of a combustible gas or liquid a vapour cloud is formed which disperses into the surroundings. When an ignition source is met a flame front will be generated that propagates through the cloud. When this flame front encounters obstacles or other forms of semi-confinement the flame speed is enhanced significantly. That is the moment when the explosion is generated; this explosion process will have a hemispherical character. Nearly all the combustible material in the cloud will then contribute to the blast wave.

This information is derived, as previously described, from accidents with the aid of some simple and some more complicated assumptions. This study was performed in order to see whether an alternative approach to the solution of this complicated field of interest would lead to useful results. It has been shown that valuable results can be obtained, the most important ones of which are presented in this paper.

List of symbols

c_0	speed of sound	(m/s)
E	combustion energy of stoichiometric mixture	(J/m^3)
I	blast wave impulse	(Pa s)
I_S	scaled impulse	(−)
L	characteristic explosion length	(m)
Δp	blast wave peak overpressure	(Pa)
P_S	scaled peak overpressure	(−)
P_0	ambient pressure	(Pa)
R	distance	(m)

t_+ positive phase duration (s)
T_S scaled positive phase duration (--)

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