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# THE MULTI-ENERGY METHOD

# A FRAMEWORK FOR VAPOUR CLOUD EXPLOSION BLAST PREDICTION

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## Summary

Partial confinement is a major cause of blast in vapour cloud deflagrations. Criteria to identify partial confinement in vapour clouds are indicated. A method for blast prediction is proposed, which fully reflects characteristic features of vapour cloud explosions. Its use is demonstrated in a case study and its applicability is discussed.

## 1. Introduction

The many vapour cloud explosions from the past [1] clearly indicate the need to reckon with this problem of industrial safety. A vapour cloud explosion is a possible consequence of an incident causing a release of a combustible into the atmosphere and subsequent ignition. A current method for explosion analysis is to model the observed blast effects by means of high-explosive blast. Although blast characteristics of high-explosive detonations and gas explosions differ fundamentally, such a procedure has proved to be a workable method even for many vapour cloud explosions. The blast observed is thought to be replaced by the blast from an equivalent amount of high-explosive causing a comparable damage pattern. Many vapour cloud explosions have been analysed in this way over the years. However, a proper correlation between the amounts of combustion energy involved in the various vapour cloud explosions and the equivalent amounts of high-explosive to model their blast effects could not be found [2]. Apparently the explosive behaviour of a vapour cloud is not only determined by the nature of the fuel air mixture itself but mainly by external factors. Despite the absence of criteria to incorporate such factors, the abovementioned methods are often recommended to predict possible blast effects in fictitious accident scenarios as part of hazardous materials risk assessment [3—6]. It is obvious that the results cannot be very satisfactory. To offset these deficiencies to some extent a gas explosion model was introduced some years ago [7]. A blast prediction method based on this model has been used in The Netherlands for some years now [8]. With this method an estimate of blast effects can be made, dependent on the presence of partial confinement and obstacles in the vapour cloud. However, the influence of such factors on possible blast effects from vapour cloud explosions was still poorly described. In this paper the concept of partial confinement is specified further and a method for blast prediction is drawn up that reflects its interference in vapour cloud explosions [9, 10].

## 2. Partial confinement

Theoretical and experimental indications [11, 12] suggest that blast of substantial strength is not to be expected from deflagrative combustion of large flat hydrocarbon—air clouds in the open field. Contrarily, substantial blast effects may be generated only in places where certain boundary conditions are met by the combustion process [12]. The nature of these boundary conditions may be revealed by simple reasoning. Blast is generated when a combustion process is so fast that an overpressure is produced. Overpressure is the net result of two competing aspects, viz., pressure build-up by combustion and pressure relief by expansion. It is obvious, therefore, that a higher overpressure is developed in a combustion process as its free expansion is more and more hampered by rigid boundaries, the more so as the combustion rate is enhanced continually by the flow structure that is induced by the confining boundaries. This simple concept enables the indication of systems of rigid boundaries which are able to generate blast:

*Dense spatial configurations of objects.* Such systems hamper free expansion by aerodynamic drag while inherently a flow structure (turbulence and shear) is induced that enhances the combustion at an ever increasing rate. This is illustrated by the fact that many vapour cloud explosions in the past occurred in compactly built process equipment in refinery or chemical plants. For the same reason piles of crates filled with bottles must be regarded as explosion hazardous in this context.

*Configurations of parallel planes.* Expansion is totally obstructed in one direction by such systems. The expansion flow is forced along the planes that generate a combustion-enhancing flow structure. Illustrative for this case is the fact that an important category of vapour cloud explosions in the U.S.A. occurred in crowded railroad shunting yards. It is easy to imagine that heavy blast producing conditions are found underneath groups of concentrated wagons.

*Tube-like configurations of rigid boundaries.* This case follows naturally from the previous one and is clearly demonstrated by any simple explosion experiment in a pipe. Therefore, constructions like subways, culverts and sewage systems must be regarded as possible blast generators in vapour cloud explosions.

This short enumeration indicates various ways in which partial confinement may manifest itself. The exact strength of the blast, of course, is dependent both on geometric details of the partially confining systems and the nature of the combustible involved. A rough impression of this strength may be gained on the basis of experimental data including those in Refs. [12—14].

## 3. The Multi-Energy Method

### *3.1 Basic idea*

The concept of a vapour cloud explosion resulting from the foregoing has important consequences for the modelling of its blast. Strong blast is generated only in places characterized by a considerable degree of partial confinement while other, usually large parts of the cloud just burn out without any significant contribution. It is obvious that the modelling of such a concept by means of one single blast wave, as is usual by current methods, will not be very satisfactory. A much better result is obtained if the blast produced by the various sources should be modelled separately.

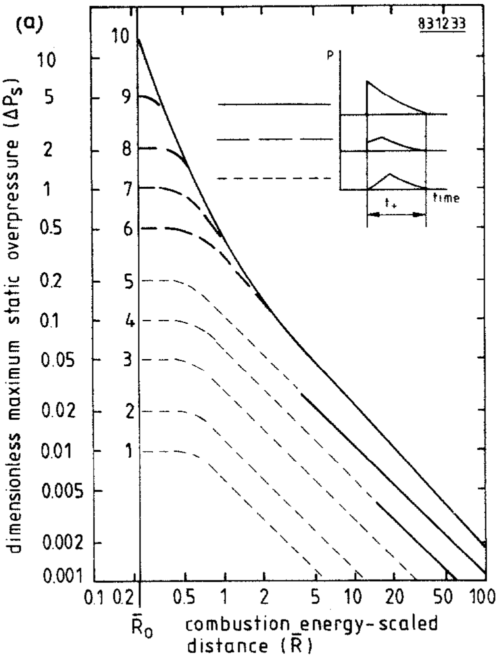
### *3.2 Blast model*

To represent blast a model is required. In this method the blast produced by a hemispherical, steady flame speed, stoichiometric hydrocarbon—air explosion is used for this purpose. Such blast has been numerically simulated by means of a Flux-Corrected Transport code [15]. Figures 1a—1c represent the blast wave properties (peak static overpressure, peak dynamic pressure and positive phase duration) as functions of distance. Sachs scaling has been used to present the relations in dimensionless form. To simplify their use the results have been formalized somewhat without losing significant information.

The model blast exhibits basic features of gas explosion blast. The initial strength of the blast (initial value of the blast properties) is a variable and is indicated by a number ranging from 1 for insignificant strength to 10 for gaseous detonation. In addition an indication for the blast wave shape has been given. High-strength blast consists of a shock wave represented by solid lines. Contrarily, low-strength pressure waves are indicated by dashed lines. They may steepen up to shock waves in the far field. There is another basic feature which is of particular importance for blast modelling. At a certain distance the blast is nearly independent of its initial strength in case this strength is higher than number 6 or 7. This feature enables us to model blast effects outside the cloud with particular accuracy whenever the assumption of high initial strength is justified. The modelling of a gas explosion is realized by choosing an initial strength and substituting the amount of combustion energy involved.

### *3.3 Use of the model*

How to use this simple model to create a realistic picture of the blast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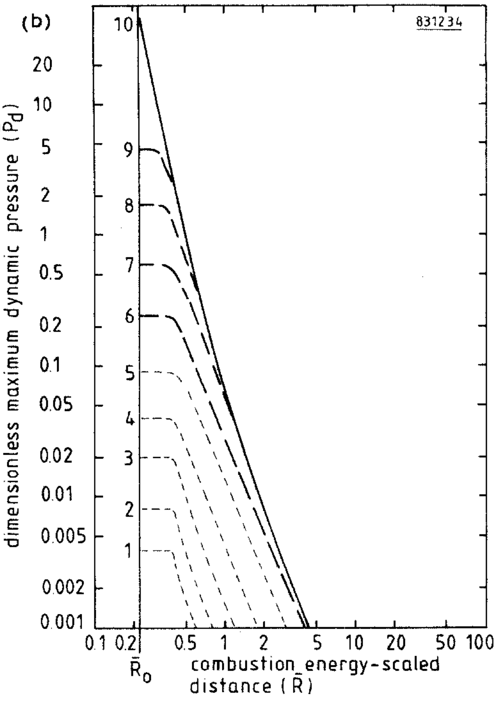
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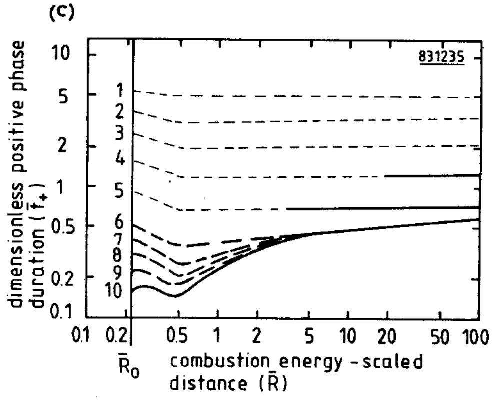

Fig. 1. Blast model for exploding hydrocarbon—air mixtures: a, peak static overpressure; b, peak dynamic pressure; c, positive phase duration. $\overline{\Delta P_s} = \Delta P_s/P_0$; $\bar{P}_d = P_d/P_0$; $\bar{t}_+ = t_+ c_0\ (P_0/E)^{1/3}$; $\bar{R} = R\ (P_0/E)^{1/3}$. $P_0$ = ambient pressure; $c_0$ = ambient velocity of sound; $E$ = combustion energy involved; $R_0$ = fuel—air charge radius.

produced by a vapour cloud explosion is the subject of this section.

The concept of partial confinement makes it possible to distinguish parts of the cloud which produce blasts of higher strength. These blasts must be graphically represented by model blasts which correspond in initial strength as well as in energy content.

So far the criteria drawn up for partial confinement do not offer a quantitative estimate of the initial strength of the blasts produced by the individual parts. However, a conservative estimate is made by assuming that their initial strengths are high, i.e., higher than number 6 or 7. Now a graphical representation of these blasts can be made by substituting the respective amounts of combustion energy into the blast model. In this way the energy-scaled relations in Fig. 1 are transformed into relations between real blast wave properties and distance. Figures reflecting average properties of stoichiometric hydrocarbon—air mixtures — concentration = 0.1 kg m$^{-3}$, heat of combustion = 3.5 MJ m$^{-3}$ — facilitate the translation of any quantity of energy, combustible or mixture into an equivalent hemispherical blast model charge radius. A result of such an operation is depicted in Fig. 2, which represents the outcome of a case study elaborated in the next chapter.

Drawing up a picture of the blast produced by the vapour cloud explosion as a whole is a matter of common sense. In case only one source of high-strength blast can be identified in an unconfined vapour cloud, this picture is rather simple. Practically always the high-strength blast dominates the contribution of the unconfined part. The interpretation of the blast is straightforward, as will be demonstrated in the case study in the next chapter. This may not be true if the energy content of the high-strength source is extremely small, relatively. In that case, however, the high-strength blast has no significance outside the cloud boundaries in general. The blast picture may become more complicated if more than one blast source can be distinguished in the vapour cloud. However, since flame propagation through the unconfined parts of the cloud is relatively slow, it is extremely unlikely for the sources to be initiated at the same time. The blast produced by the vapour cloud explosion as a whole consists of more than one blast wave decaying separately and more or less independently in space. In this case a separate interpretation of these waves is the obvious way. If from a conservative point of view it may not be excluded that the waves overtake, the resultant blast properties are found from one high-strength charge with an energy content of the various sources together.

This is certainly the way in case various partially confining systems in the cloud are situated so close together that their internal combustion processes must be assumed to interact.

## 4. The Flixborough explosion — A case study

Since a more or less quantitative indication of partial confinement on the scene of the accident is required only the very best documented vapour cloud explosions lend themselves for a Multi-Energy reconstruction of their blast effects. The Flixborough explosion, therefore, offers one of the best opportunities for this purpose. Various publications, including Refs. [2, 16, 17], give a clear view on the circumstances that have been determinant for this incident. As a consequence of pipe rupture a large amount (probably more than 30 tons) of cyclohexane was released at the Nypro Ltd. plant at Flixborough (U.K.). The combustible quickly mixed with air and was ignited shortly thereafter. Damage analysis [17] indicated that process equipment was situated in the centre of the blast. Photographs [2, 17] show that the equipment can be regarded as a dense configuration of objects installed between concrete floors and therefore may be identified as explosion hazardous according to the concept of partial confinement. Apparently this was the only source of strong blast. Therefore, the blast from the vapour cloud explosion as a whole can be modelled by means of the model blasts from two fuel—air charges, viz., a low-strength charge corresponding with the slow combustion of the unconfined parts of the cloud and a high-strength charge corresponding with the explosive combustion among the process equipment. The result is presented in Fig. 2. The model blasts are dimensioned by substituting respective amounts of energy. For comparison, peak overpressure levels of the blast derived from damage analysis according to Sadee et al. [16] have been indicated as well. It appears that a fairly consistent picture can be constructed if it is assumed that only about 10 tons (about 30%) of the total amount of cyclohexane were involved in the explosive combustion. This part generated blast of high strength (i.e., higher than number 7) while the rest burned in the open, producing blast of minor strength (say number 2). A shock wave of a duration increasing to more than 0.2 seconds in the far field has been responsible for the damage, while the combustion of the unconfined parts of the cloud hardly contributed to the blast.

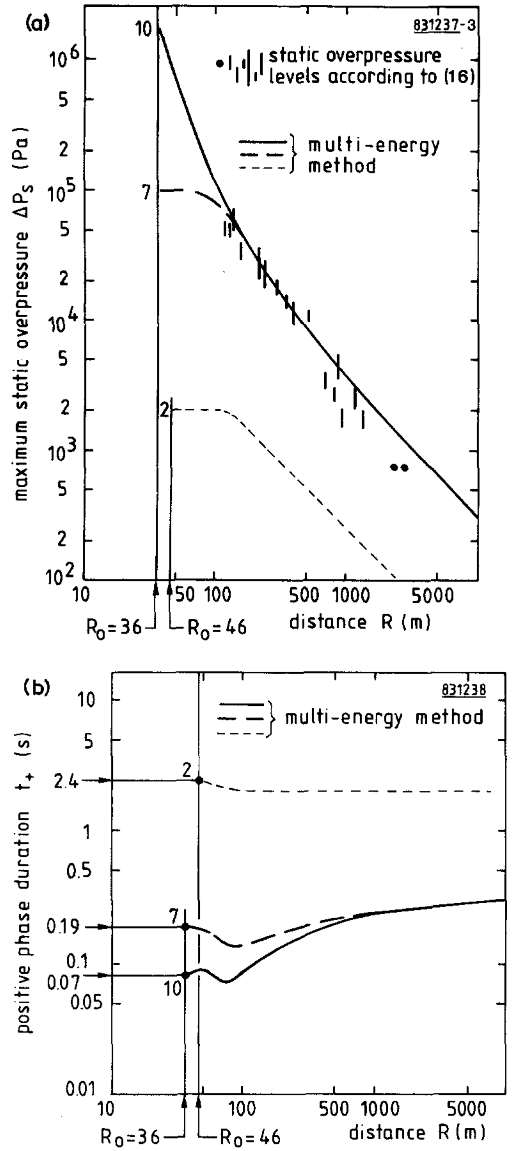

Fig. 2. Multi-Energy representation of the blast from the Flixborough explosion: a, peak static overpressure; b, positive phase duration.

Recovery of peak overpressure levels from damage, however, is difficult and therefore fairly inaccurate. By employing a different set of criteria for instance, Giesbrecht et al. [18] estimated markedly lower overpressures, in particular for the severe damage in the vicinity of the blast centre. On the basis of these overpressures the part of the total combustion energy responsible for the major blast turns out to be considerably smaller. This may be seen as an indication that the combustion energy of the vapour present among the process equipment is a good measure for the amount of energy to be used for modelling the blast.

It is interesting to note that the Multi-Energy representation of blast enables us to define a very straightforward vapour cloud explosion yield.

## 5. Applicability

The case study clearly demonstrated the possibilities of the Multi-Energy concept in vapour cloud explosion analysis. The suggested vapour cloud explosion yield could be useful in this respect. On the other hand, the criteria for partial confinement employed within the Multi-Energy framework enable the quantification of the potential explosion hazard emanating from hazardous materials in dependence on their environment.

A prerequisite for the application of the Multi-Energy method in this simple form is, however, that the possibility of vapour cloud detonation can positively be excluded. In a vast majority of cases this is justified because, inherent to the process of atmospheric dispersion, the concentration distribution in the cloud is characterized by fluctuations which prevent a possibly initiated detonation from being propagated. However, vapour cloud detonation cannot be excluded under any circumstances. If the vapour dispersion is very slow because of calm atmospheric conditions and/or an environment in which the vapour tends to linger (e.g., brushwood, a valley) a detonable concentration distribution may arise during a limited span of time and preferably in an area around the cloud's centre [19]. If during this time the cloud is ignited and deflagration—detonation transition takes place somewhere under the influence of partial confinement a substantial part of the cloud may participate in the subsequent detonation. Such an exceptional and unfortunate coincidence may explain the heavy blast observed in the Port Hudson incident. A propane cloud exploded violently while conditions required for deflagrative blast generation (partial confinement) seem to have been absent [20, 21].

The nature of the many vapour cloud explosions enumerated in the literature suggests that a more or less integral vapour cloud detonation can be regarded as quite unlikely. In view of the above this is conceivable as long as it concerns the most current hydrocarbons which are usually transported and stored in large quantities. On the other hand it is to be expected that coincidence of conditions required for vapour detonation is much more readily obtained for relatively high-reactive hydrocarbons like acetylene or ethylene oxide.

## 6. Conclusions

Partial confinement is a major cause of blast in vapour cloud deflagrations. Not only the combustible itself but mainly the environment in which it is released is the determinant factor for explosion hazard.

A prediction method for vapour cloud explosion blast effects that takes account of this factor is proposed. This method takes full advantage of basic gas explosion properties which enable the modelling of blast outside the cloud boundaries with particular accuracy whenever its initial strength is high.

In general, the damage caused by vapour cloud explosions can be explained by assuming explosive combustion of only a small part of the total amount of combustible involved. The large scatter in high-explosive equivalencies referred to in the Introduction is indicative of this. The Multi-Energy representation of blast fully reflects this characteristic feature of vapour cloud explosions.

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