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Methods for vapour cloud explosion blast modelling

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Abstract

The potential explosion hazard of fuels is quantified by methods in which the explosive potential of a flammable fuel–air mixture is expressed as an equivalent explosive charge whose blast characteristics are known. In this paper, the two most current methods are described and demonstrated in a simple case study. TNT-equivalency methods have been widely used for this purpose for a long time now. Generally speaking, TNT-equivalency methods state a proportional relationship between the quantity of fuel available and the weight of a TNT charge expressing the cloud's explosive potential. However, fundamental and practical objections are met if the TNT-equivalency concept is used for vapour cloud explosion hazard assessment. To some extent, these difficulties are remedied in an alternative approach, the multi-energy method. In the multi-energy method, a flammable fuel–air mixture is considered to be explosive only if it is in a partially confined, congested or obstructed area in the cloud. The explosive potential of the fuel–air mixture in the various partially confined, congested or obstructed regions can be expressed as a corresponding number of equivalent fuel–air charges. The multi-energy concept is shown to be a flexible concept which makes it possible to incorporate current experimental data and advanced computational methods into the procedure of vapour cloud explosion hazard analysis.

1. Introduction

The long list of vapour cloud explosions from the past indicates that the presence of a quantity of fuel constitutes a potential explosion hazard. If a quantity of fuel is released, it will mix with air and a flammable vapour cloud may result. If the cloud meets an ignition source, the flammable mixture will be consumed by a combustion process which, under appropriate conditions, may develop an explosive intensity and heavy blast. Therefore, safety measures are desirable.

Safe stand-off distances should be exercised between locations where large quantities of fuels are stored or handled and places where people live or work.

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Control buildings at chemical plants or refineries and safety related structures of nuclear power plants, for instance, should be designed in such a way that they can withstand the destructive power of a vapour cloud explosion in their vicinity.

To establish fair premium rates, underwriters need to know the property damage potential of a quantity of fuel. For all these purposes, blast modelling methods are required by which the explosive potential of a fuel–air cloud present in some given environment can be quantified. Such methods express the explosive power of a vapour cloud as an equivalent explosive charge whose blast characteristics are known. TNT-equivalency methods, for instance, state a proportional relationship between the quantity of fuel in the cloud and the weight of an equivalent TNT-charge expressing its explosive power. Up to this day, TNT-equivalency methods are widely used for this purpose. However, TNT-equivalency methods are becoming progressively less satisfactory as the understanding of blast generation vapour cloud explosions increases.

Methods which utilize an equivalent fuel–air charge to express the potential explosive power may overcome the imperfections of TNT-equivalency blast modelling to some extent. Such a charge can be characterized by, for instance, applying the multi-energy philosophy which reflects the current understanding of vapour cloud explosions. In addition, the multi-energy concept makes it possible to incorporate current experimental data and advanced computational fluid dynamics into the procedure of vapour cloud explosion hazard assessment.

In this paper, both these most current methods are described and briefly demonstrated in a simple case study – a vapour cloud explosion hazard assessment with regard to a storage site for liquefied hydrocarbons.

1.1 Statement of the problem

A view of the storage site is represented in Fig. 1. Three storage spheres containing liquefied propane are situated next to a large butane tank of 50 m

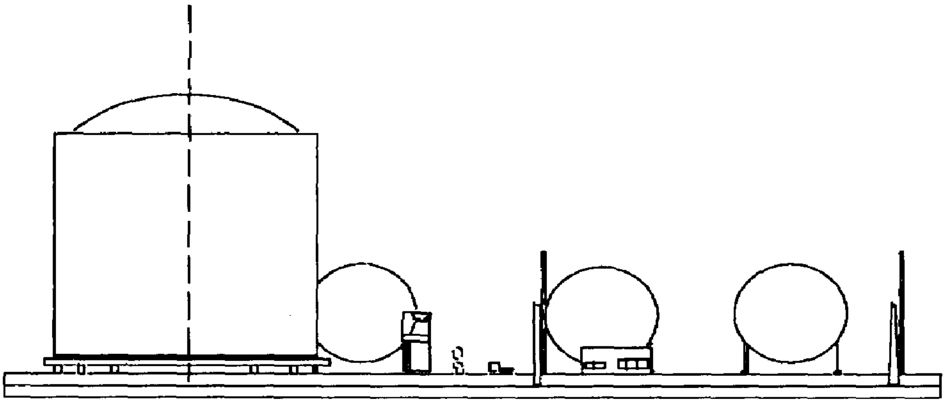


Fig. 1. View of a storage site for liquefied hydrocarbons.

diameter and 30 m height. To diminish heat inflow from the soil, the butane tank is placed 1 m above the earth's surface on a concrete pylon forest. In this environment a massive release of 20 tons of propane is anticipated. What blast effects can be expected if the propane forms a large flammable cloud blanketing the storage site and meets an ignition source?

For a complete description of blast loading, the full pressure–time history of the blast wave should be specified at any location in a vapour cloud explosion's environment. A blast model, on the other hand, defines a blast wave only in terms of the peak overpressure, the positive phase duration and the positive impulse, while the under-ambient pressure effects are neglected. These blast parameters are minimally required to calculate the behaviour of structures under blast loading or to assess explosion damage. Figure 2 plots idealized

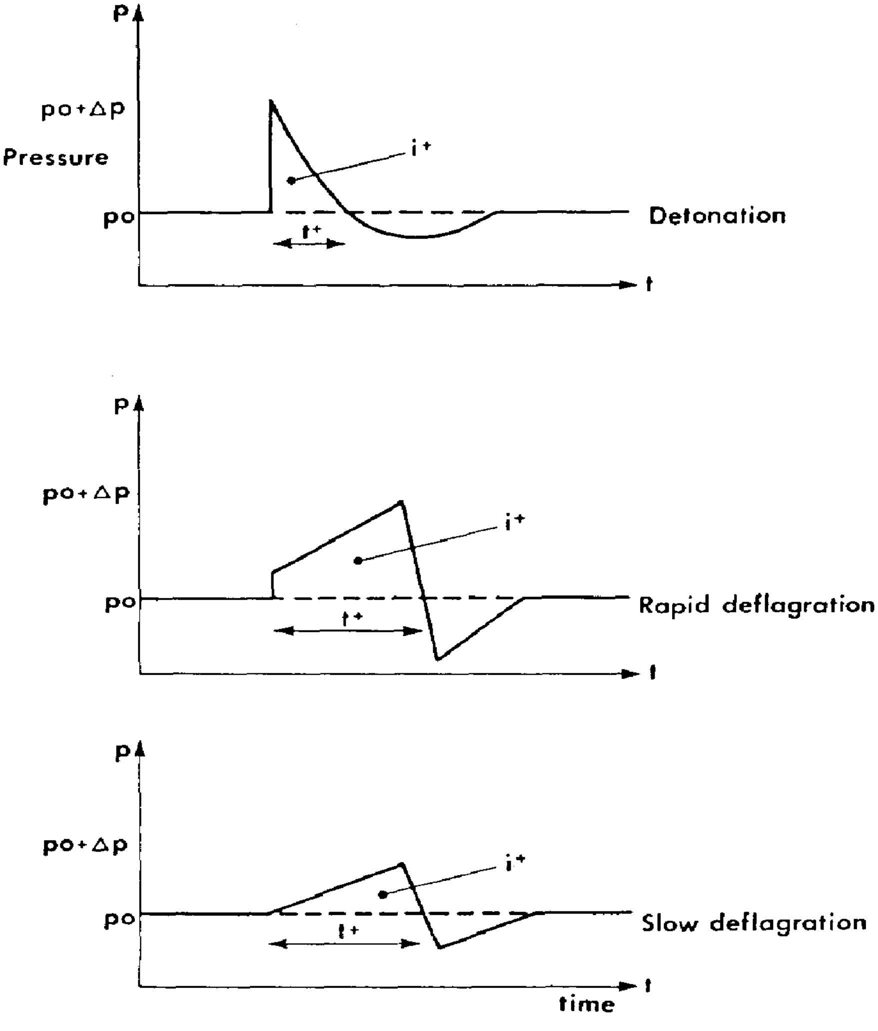


Fig. 2. Ideal blast wave structure (P_0=ambient pressure, Δp=peak overpressure, t^+ =positive phase duration, i^+ =positive impulse).

blast wave shapes and points out the parameters defining the blast load for structures.

2. TNT-equivalency methods

2.1 The basic concept

For a long time now, the military has been interested in the destructive potential of high-explosives. Therefore, extensive experimental data on the relation between TNT and damage have been available for many years. Consequently, it is quite obvious that the explosive power of accidental explosions, deduced from the damage patterns observed, was expressed as equivalent TNT-charge weights. Because the quantification of the potential explosive power of fuels was a necessity long before the mechanisms of blast generation in vapour cloud explosions were understood, it is fully comprehensible that the TNT-equivalency concept was also utilized to make predictive estimates for vapour cloud explosion hazard assessment.

Basically, the use of TNT-equivalency methods for blast predictive purposes is very simple. The available combustion energy in a vapour cloud is converted into an equivalent charge weight of TNT according to:

$$W_{\mathrm{TNT}} = \alpha_{\mathrm{e}}\, W_{\mathrm{f}} Q_{\mathrm{f}} / Q_{\mathrm{TNT}}$$

where α_{e} denotes the TNT-equivalency, W_{TNT} the equivalent weight of TNT, W_{f} the total weight of fuel in cloud, Q_{f} the heat of combustion of fuel, and Q_{TNT} the heat of explosion of TNT (4.12–4.69 MJ/kg).

If the equivalent charge weight is known, the corresponding blast characteristics can be read from Fig. 3, which represents experimental TNT-blast data, an excerpt from the military technical manual TM 5-1300. Strictly speaking, the problem of vapour cloud explosion blast modelling is reduced to the determination of an appropriate value for the TNT-equivalency.

2.2 Blast modelling

Over the years many companies and authorities each developed their very own approach with regard to the use of the TNT-equivalency concept in vapour cloud explosion hazard assessment. Because all these methods differ only in details, only one of them is described here.

Within the framework of safety studies of nuclear power plants, where special importance was attached to the assessment of dangers which could arise from nearby industrial activities, in references [2–4] a statistical analysis is performed on more than 120 damage points of 23 accidents. A wide distribution of TNT equivalencies (0.02%–15.9%) with a median value of 3% was observed. 97% of the cases was covered by a TNT equivalency lower than or equal to 10%, while the mean value observed was a TNT equivalency of 4%, covering 60% of the cases.

The value of 10% corresponds approximately to a TNT equivalent of 1 kg of TNT for every kg of hydrocarbon released and to 5 kg of TNT for every kg of hydrocarbon mixed with air between the flammability limits. The latter value can be used if the flammable portion of the cloud is determined by means of dispersion calculations.

In addition, the analysis in references [3] and [4] showed that ignition delay and the presence of objects in the cloud are important factors in vapour cloud explosions and that blast effects are often asymmetric and directional.

TNT equivalency methods for vapour cloud explosion modelling should only be used for the assessment of blast effects in the far-field where the overpressure level is less than 30 kPa. In the near-field their use can lead to the

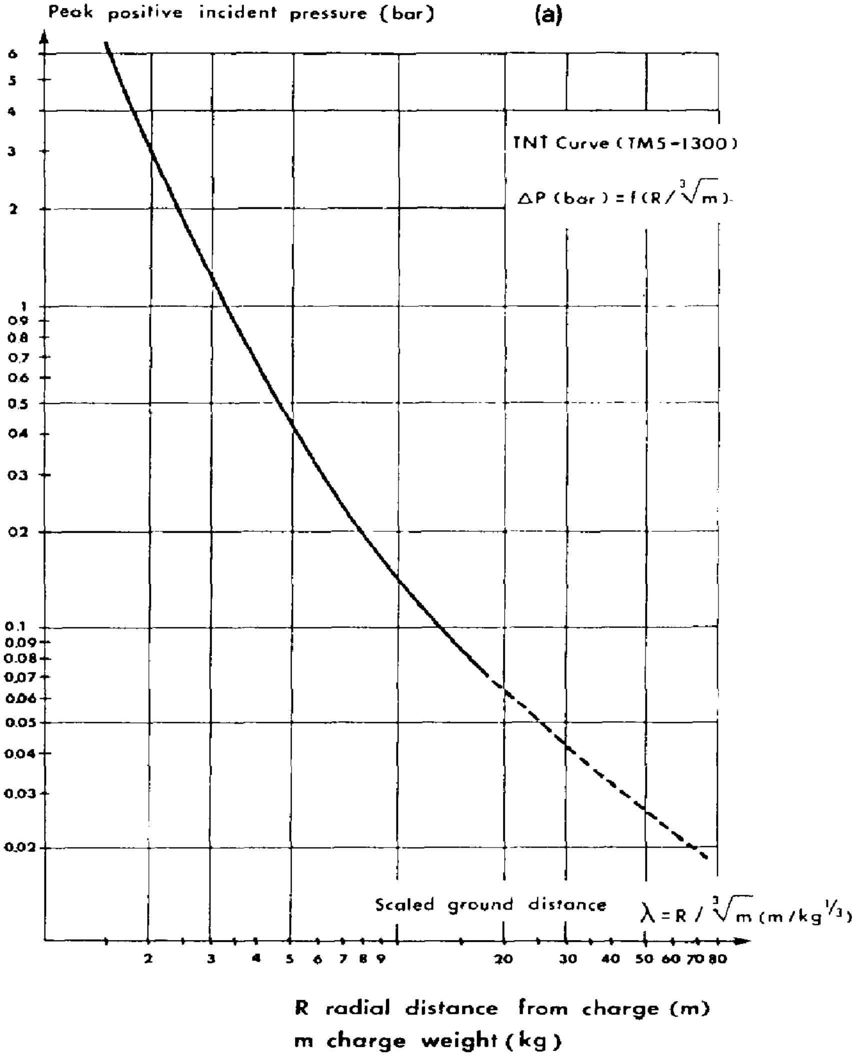
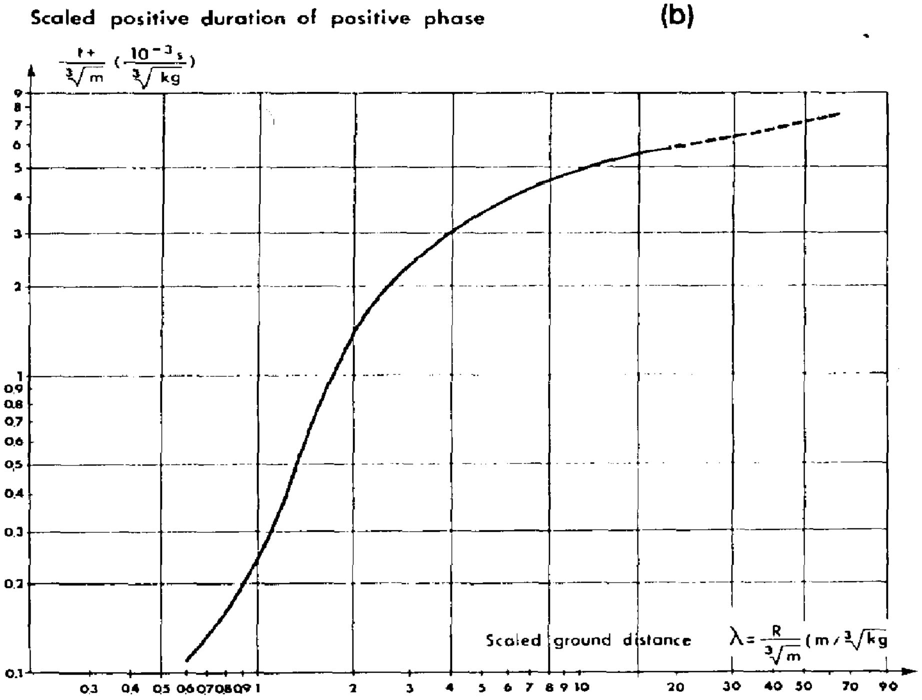


Fig. 3. (a) Blast peak incident overpressure for a hemispherical TNT charge at sea level [1]. (b) Blast positive phase duration for a hemispherical TNT charge at sea level [1]. (c) Blast positive incident impulse for a hemispherical TNT charge at sea level [1].



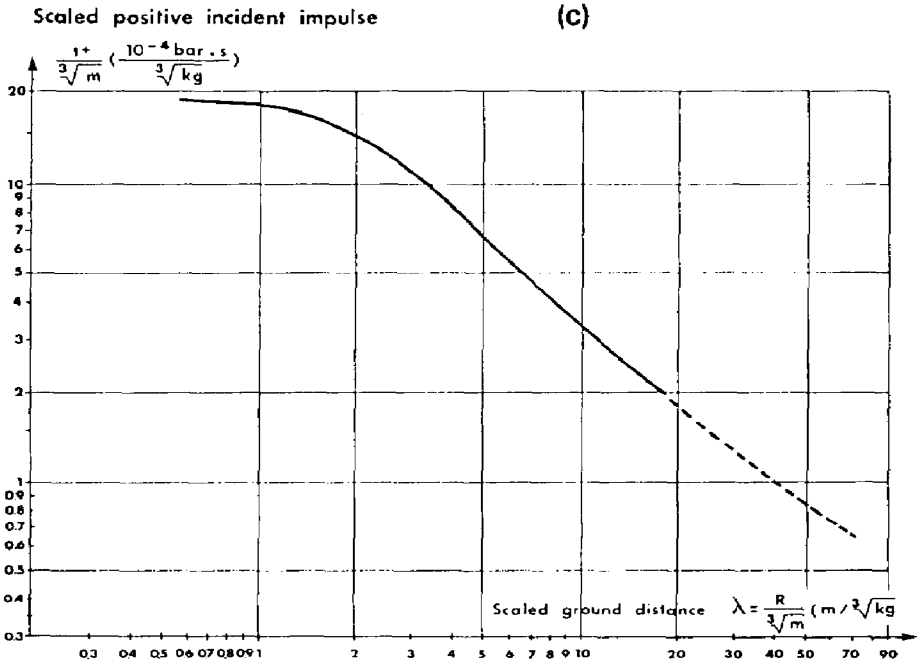


Fig. 3. Continued.

overdesign of structures. Note that a French Authority Safety Rule [5] recommends the 10% equivalency for safety calculations and that the French Chemical Industry [6] recommends the 4% equivalency, both based on the full amount of fuel released.

TABLE 1

Comparison of blast characteristics modelled by both TNT-equivalency methods and the multi-energy method

Overpressure (kPa)	TNT equivalency				Multi-energy method energy	
	10%		4%		7330 MJ	
	Distance (m)	Positive phase duration (ms)	Distance (m)	Positive phase duration (ms)	Distance (m)	Positive phase duration (ms)
30	165	100	120	74	57	40
20	210	117	155	86	75	45
10	355	138	260	102	120	50
7	490	152	360	112	160	53
5	680	163	500	120	210	55

Application of the above recommendations to the case study on the liquefied hydrocarbons storage site results in the conclusion that the explosive potential of the 20 tons of propane can be expressed as:
(a) a 20 ton charge of TNT with a confidence level of 97%;
(b) an 8 ton charge of TNT with a confidence level of 60%.
The blast characteristics in the form of blast overpressures and positive phase durations at various distances to the charges are summarized in Table 1 together with the results of the multi-energy blast modelling.

2.3 Discussion

The basic assumption in TNT-equivalency methods – a relation between the amount of fuel available in the cloud and the TNT-charge weight expressing the cloud's explosive potential – is most questionable. This is reflected by the wide range of TNT equivalencies found if a large number of vapour cloud explosion incidents, involving only fuels whose heats of combustion are of the same order of magnitude as hydrocarbons, is analysed [3, 4, 7, 8].

Nevertheless, the TNT-equivalency concept makes it possible to model the blast effects of a vapour cloud explosion in a very simple and practical way. The great attractiveness of TNT-equivalency methods is the very direct, empirical relation between a charge weight of TNT and the attendant structural damage. Therefore, TNT equivalency is a useful tool if the property damage potential of vapour clouds is the major concern.

Values for the TNT equivalency, recommended for use in vapour cloud explosion hazard assessment, are deduced by statistical analysis from the damage observed in a limited number of major vapour cloud explosion incidents. From the wide distribution of TNT equivalencies observed, characteristic values such as an average (4%) and an approximate upper limit (10%)

were recommended to be used for predictive purposes [3, 4]. The average value of 4% is very near the TNT equivalency in the distribution where the majority of cases are found, i.e. a TNT equivalency of 4% corresponds to "an average major incident". Undoubtedly, "an average major incident" represents a situation where an accidental release of fuel is most likely such as, for instance, the site of a refinery or chemical plant or the site of a crowded marshalling yard during operations. Strictly speaking, by using an average value of the TNT equivalency, "average major incident conditions" are extrapolated to an actual situation. Therefore, TNT-equivalency methods give a reasonable estimate of far-field blast effects only if the actual conditions correspond more or less to "average major incident conditions".

TNT blast is a poor model for gas explosion blast. While a TNT charge produces a shock wave of a very high amplitude and a short duration, a vapour cloud explosion produces a blast wave, often shockless, of lower amplitude and longer duration. If the blast modelling is the starting point for the computation of structural response for, for instance, the design of blast resistant structures, TNT blast will be a less satisfactory model. Then the shape and the positive phase duration of the blast wave are important parameters which should be considered and the use of a more appropriate blast model is recommendable.

A practical value for TNT equivalency is an average, based on a wide statistical distribution of TNT equivalencies found in practice. As a consequence, a predictive estimate with TNT equivalency on the basis of an average value for the TNT equivalency has a very limited statistical reliability. A more deterministic estimate of blast effects is possible if a parameter could be found which correlates with the process of blast generation in vapour cloud explosions. In the multi-energy method such a parameter is introduced.

3. The multi-energy method

3.1 The basic concept

Presently, the belief is gaining ground that it is hardly possible to detonate an unconfined vapour cloud. The point is that the inhomogeneity of the fuel–air mixture, which is inherent to the process of atmospheric dispersion, prevents a possible detonation wave from propagating [9]. The heavy vapour cloud explosion on December 7, 1970 at Port Hudson (MO), USA where a substantial part of a large unconfined propane–air cloud detonated [10], should be blamed on a highly exceptional coincidence of circumstances. Lingering in a shallow valley under calm atmospheric conditions, the dense propane–air mixture had the opportunity to homogenize sufficiently by molecular diffusion during an exceptionally long ignition delay [9]. Therefore, in a vast majority of cases, the assumption of deflagrative combustion is a sufficiently safe approach in a vapour cloud explosion hazard assessment.

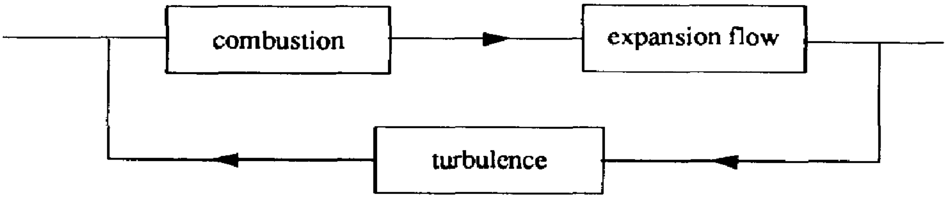


Fig. 4. Positive feedback, the basic mechanisms of a deflagrative gas explosion.

For blast generation in deflagrative premixed combustion, turbulence generating (boundary) conditions are required. These boundary conditions trigger a positive feedback coupling in the process of flame propagation by which it develops more or less exponentially both in speed and pressure. A deflagrative gas explosion may be well defined as a process of combustion driven expansion flow in which the turbulent structure of the flow field is acting as an uncontrolled positive feedback (Fig. 4).

The consequence is that a turbulence generating environment is required for the development of explosive blast generating combustion. This statement has important consequences for the concept of a vapour cloud explosion which underlies the method of blast modelling. This basic concept, called the multi-energy concept, states that blast is generated in vapour cloud explosions only where the flammable mixture is partially confined and/or obstructed while, on the other hand, the unconfined/unobstructed mixture hardly contributes [11]. This concept is increasingly supported by both small-scale and large-scale experiments, including references [12–16]. So, contradictory to more conventional methods, in which a vapour cloud explosion is regarded as an entity, in the multi-energy concept a vapour cloud explosion is rather defined as a number of sub-explosions corresponding with the various partially confined/obstructed areas in the cloud.

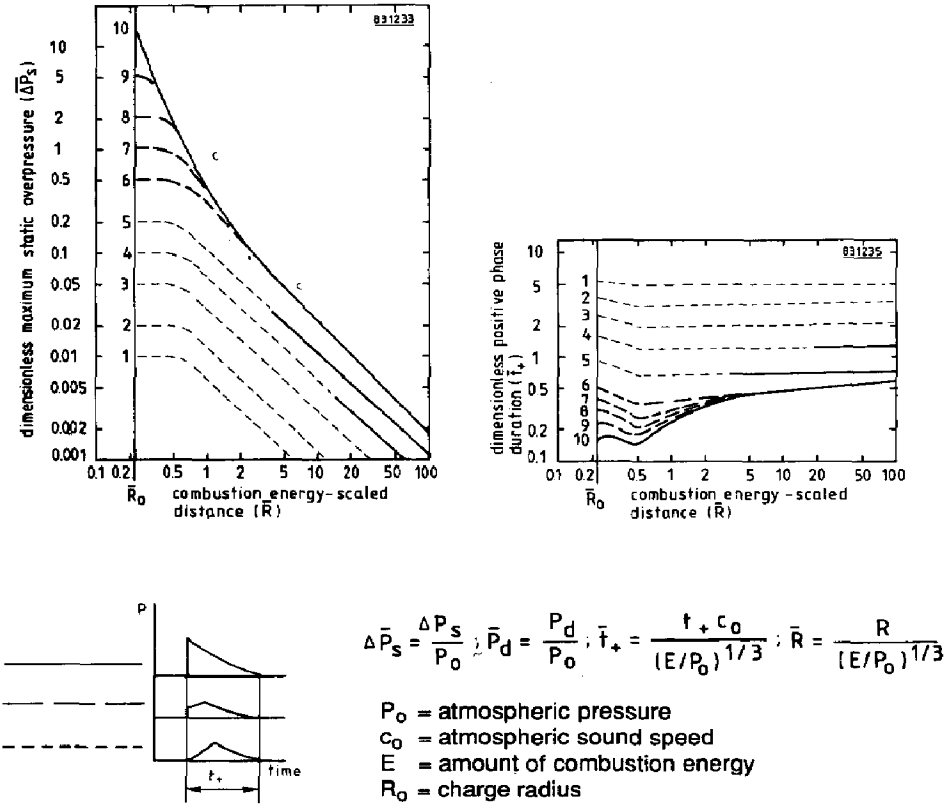
3.1.1 Application

The space underneath the storage tank is the only location at the storage site where blast generating boundary conditions are found. For the space underneath the storage tank is an outstanding example of a combination of partial confinement by extended parallel planes and obstruction by the pylon forest which pre-eminently is a turbulence generating environment. On the other hand, the space underneath and in between the propane spheres is relatively open and unobstructed. Therefore, the multi-energy concept applied to this situation indicates that, if the entire storage site is blanketed in an extended flammable cloud, only the explosive combustion which develops underneath the storage tank is responsible for the blast produced upon ignition of the cloud. The blast effects produced by this gas explosion are mainly determined by the quantity of combustion energy present in the space underneath the butane tank and the intensity of the combustion process. Both are primarily determined by the size, shape and nature of the partially confined and obstructed space. The reactivity of the fuel–air mixture is a factor indeed, but of secondary influence.

3.2 The blast model

To bypass the imperfections of TNT blast as a model for gas explosion blast, in the multi-energy method fuel–air charge blast is used for this purpose. Figure 5 shows the peak overpressure as well as the positive phase duration of the blast wave, produced by a hemispherical fuel–air charge of radius R_0 at the earth's surface, dependent on the distance to the blast centre in a Sachs-scaled representation. This blast model is generated by numerical simulation of spherical steady flame speed gas explosions. The heat of combustion of the fuel–air mixture was assumed to be 3.5 MJ/m^3, which is representative for an average stoichiometric hydrocarbon–air mixture.

The blast model reflects basic features of gas explosion blast. The initial blast strength is a variable expressed as a number ranging from 1 for insignificant to 10 for detonative strength. The initial blast strength can be defined as a consistent set of blast parameters at the location of the charge radius R_0. In addition, the model gives an indication for the blast wave shape. It is interesting to note that the detonative blast characteristics are in good agreement with experimental data according to [17].



$$\Delta\bar{P}_s = \frac{\Delta P_s}{P_0} \; ; \; \bar{P}_d = \frac{P_d}{P_0} \; ; \; \bar{t}_+ = \frac{t_+ c_0}{(E/P_0)^{1/3}} \; ; \; \bar{R} = \frac{R}{(E/P_0)^{1/3}}$$

P_0 = atmospheric pressure
c_0 = atmospheric sound speed
E = amount of combustion energy
R_0 = charge radius

Fig. 5. Hemispherical fuel–air charge blast model [11].

The blast produced by the gas explosion underneath the storage tank can now be modelled by the blast from an equivalent hemispherical fuel–air charge which is characterized by a size and a strength.

3.3 *The charge size*

A safe and conservative estimate for the size of the charge can be made by assuming that the whole space underneath the tank is filled with a stoichiometric mixture which wholly contributes to the blast. Consequently, the radius of the hemispherical charge is approximately 10 m which corresponds with an energy of 7330 MJ (heat of combustion = 3.5 MJ/m^3).

3.4 *The charge strength*

A reasonable estimate for the strength of the blast is a more difficult problem which can be overcome in a variety of ways depending on the accuracy required.

3.4.1 *Safe and conservative data*

A safe and conservative estimate for the strength of the charge for near-field blast effects is 10, i.e. the assumption of detonative combustion (see Fig. 5). For far-field blast effects, on the other hand, the assumption of any strength higher than or equal to number 6 is sufficient because far-field effects are independent of the charge strength whether the explosion was a strong deflagration (number 6) or detonation (see Fig. 5).

If such a safe and conservative approach results in unacceptably high overpressures, a more accurate estimate for the initial blast strength may be found by consulting the growing body of experimental data on gas explosions or by performing an experiment tailored for the situation in question.

3.4.2 *Experimental data*

Since more than a decade ago, an increasing amount of experimental data (both on laboratory and full scale) on gas explosions in partially confined/obstructed environments becomes available. Many parameters were varied such as: degree of confinement, geometry, obstacle parameters, fuel reactivity and mixture composition. This growing body of experimental data offers the opportunity to compare actual situations with experimental data. It would be desirable to identify and collect these data, to structure a data base and to develop access to this information. It would be highly interesting, for instance, if these data could be parameterized, i.e. if the blast strength could be correlated to parameters such as: degree of confinement, obstacle configuration parameters and fuel reactivity.

For a good interpretation of the mostly small-scale experiments, a good understanding of scale effects in gas explosions is a necessity.

Experiments which could give a first indication of the overpressure to be expected from the gas explosion in the space underneath the butane tank are reported by Van Wingerden [14]. A large number of obstacle configurations between parallel planes was investigated with regard to their blast generating capabilities. On the basis of these experimental data, a first estimate for the overpressure, generated underneath the butane tank, of 50 kPa to 200 kPa would be reasonable.

In addition, a good understanding of scaling effects offers the possibility of physical modelling, i.e. the estimation of overpressures by an experiment in a scaled down version of the actual situation.

3.4.3 Computational data

An approach which seems very promising for the near future is numerical simulation with advanced computational fluid dynamic computer codes such as FLACS [18, 19] and REAGAS [20, 21]. These codes are capable of simulating the basic mechanism of a gas explosion, the feedback coupling in the interaction of combustion, expansion flow and turbulence. Here, the REAGAS code is utilized to simulate the gas explosion in the space underneath the storage tank. The mathematical model which underlies the REAGAS code can be summarized as follows:

1. The gas dynamics is modelled as a gaseous fluid which expands as a consequence of heat addition. This is expressed in conservation equations for mass, momentum and energy.
2. The energy addition is supplied by combustion which is modelled as a simple one-step conversion process of unburnt mixture into combustion products. This is expressed in a conservation equation for the mixture mass fraction with a negative source term for the combustion rate.
3. The combustion rate, which is fully controlled by turbulent mixing of combustion products with unburnt mixture, is modelled by the Bray–Libby–Moss Unified Probability Function model [22].
4. The feedback in the interaction is closed by a k–ε model for turbulence which consists of conservation equations for the turbulent kinetic energy k and its dissipation rate ε.

The pylon forest underneath the butane storage tank was simplified into a two-dimensional obstacle environment, represented in a 130 × 65-node grid. The obstacles are placed in 11 concentric circles according to the pylon lay out (Fig. 6(a)). It is likely that the vapour cloud will meet an ignition source somewhere at the storage site outside the partially confined area. Then the combustion process in the obstacle configuration will be initiated from its edge. The present concept of the REAGAS code, however, cannot cope with edge-ignition. In an attempt to approximate an edge-ignited explosion the combustion process was initiated halfway between centre and edge. The results are represented in Figs. 6(a) and 6(b). Figure 6(a) shows the temperature distribution in the flow field at a few points of time during the development of the gas explosion. The temperature distribution is visualized by a pattern of isotherms, one for each change in temperature of 150 K. The temperature is, of course, a good indicator for the combustion process. The sequence of pictures shows a behaviour which is characteristic for gas explosions, namely, a slow start followed by a more or less exponential development in speed and pressure once the feedback coupling in the process of flame propagation is triggered.

This behaviour can be readily recognized in the overpressure transients sampled at various locations in the axis of symmetry (Fig. 6(a)). The computations show that an overpressure of more than 70 kPa is observed in location 4 (Fig. 6(a)) where the combustion process attains its highest intensity. Higher overpressures are to be expected if the combustion process would be initiated closer to the edge.

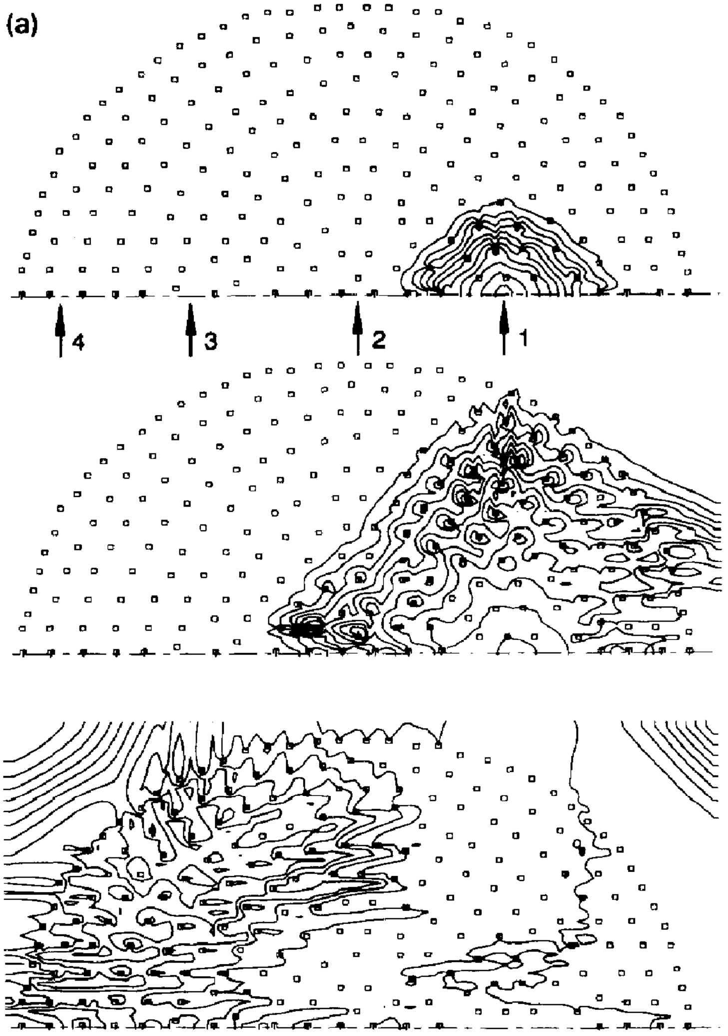


Fig. 6. (a) REAGAS simulation of a gas explosion developing in a concrete pylon forest underneath the butane storage tank. Temperature distribution visualized by an isotherm pattern, one isotherm for each change in temperature of 150 K. (b) Pressure transients sampled at four locations indicated in Fig. 6(a).

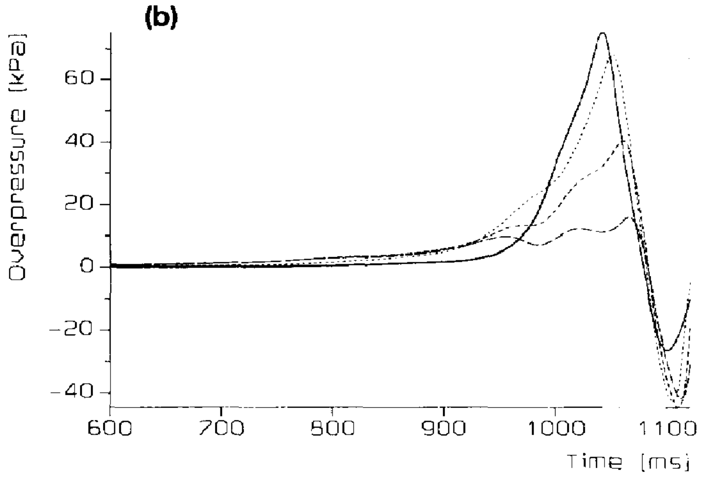


Fig. 6. Continued.

As a consequence, a maximum overpressure of approximately 100 kPa, generated by the gas explosion underneath the tank, is considered realistic. The overpressure corresponds to a blast strength of number 7 of the fuel–air charge blast model (Fig. 5).

3.5 Far-field blast effects

With the vapour cloud's explosive potential expressed as an equivalent fuel–air charge of a radius $R_0 = 10$ m ($E = 7330$ MJ) and a strength of number 7, the potential blast effects of the vapour cloud explosion can be found by substitution of these data in the Sachs-scaled fuel–air charge blast model (Fig. 5). Blast peak overpressures as well as durations of the blast wave's positive phase at several distances to the charge centre are presented in Table 1 beside the results of the blast modelling calculations on the basis of TNT-equivalency (Section 2.2).

The figures in the Table 1 show that, relative to the multi-energy method, the vapour cloud's explosive potential is strongly overestimated by TNT-equivalency methods. The problem is that conventional TNT-equivalency methods should not be used in situations such as in the present case study where the conditions at the storage site differ substantially from so-called "average major incident conditions", on which the used values for the TNT-equivalency were based (Section 2.3).

3.6 Near-field blast effects

After all, the representation of blast effects by means of a spherical model results in a highly idealized picture which may hold only for the far-field, at best. Blast effects produced by a partially confined space of such a large aspect ratio (length/height) as in the present situation are largely determined by the size of the opening through which the generated overpressure is vented from the confinement into free space. In addition, the partial confinement by extended parallel planes induces a preferential direction in the combustion process. The consequence is that the near-field blast effects are highly directional, a well-known effect in the vapour cloud explosion literature. In addition, near-field blast effects are largely influenced by the interaction with nearby structures and objects. For the gas explosion in question, the near-field blast wave propagation is largely influenced by the presence of the butane storage tank itself.

These effects can be approximated by numerical simulation. In this paper, these effects are simulated with the BLAST code [23]. This code is capable of computing blast effects by the solution of the Euler equations in a two-dimensional space. The Euler equations describe the conservation of mass, momentum and energy for inviscid flow of a perfect gas. Flux-corrected transport [24] is used to capture and preserve shock phenomena.

For the problem in question, the code is initialized with a perfect gas in the space underneath the storage tank, pressurized up to a pressure and temperature so that a 100 kPa overpressure blast wave is formed on the burst. The computation is performed in a cylindrical grid consisting of 300 × 300 nodes. The results are represented in Figs. 7(a) and 7(b). The pressure distribution in the flow field at a few consecutive points of time is represented in Fig. 7(a). The

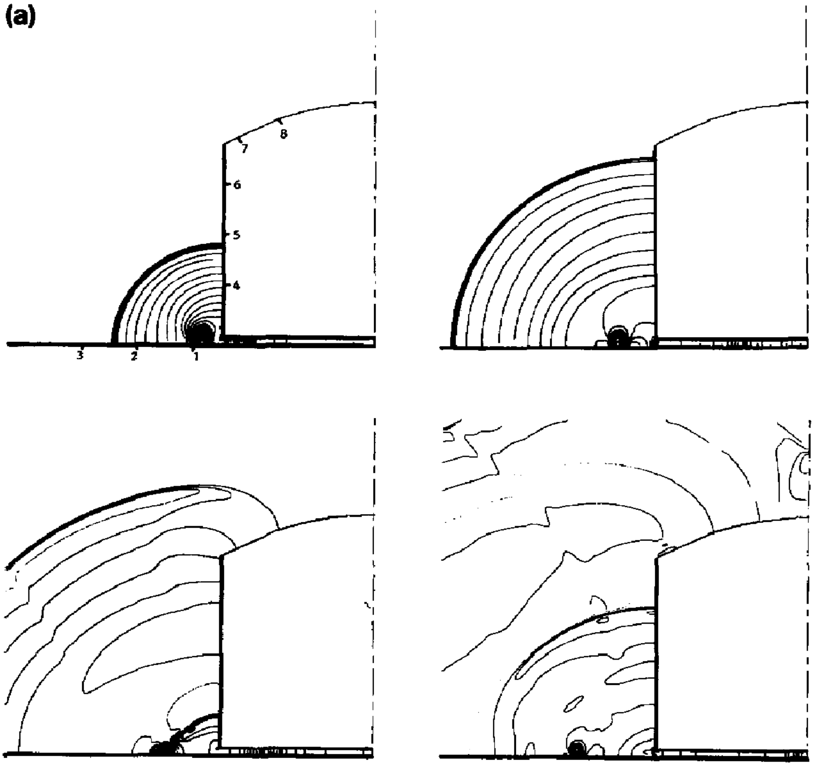


Fig. 7. (a) BLAST simulation of the near-field blast produced by the gas explosion underneath the butane storage tank. Pressure field visualized by an isobar pattern, one isobar for each change in pressure of 2.5 kPa. (b) Blast overpressures sampled at various locations in the vicinity of the gas explosion. The locations are indicated in Fig. 7(a).

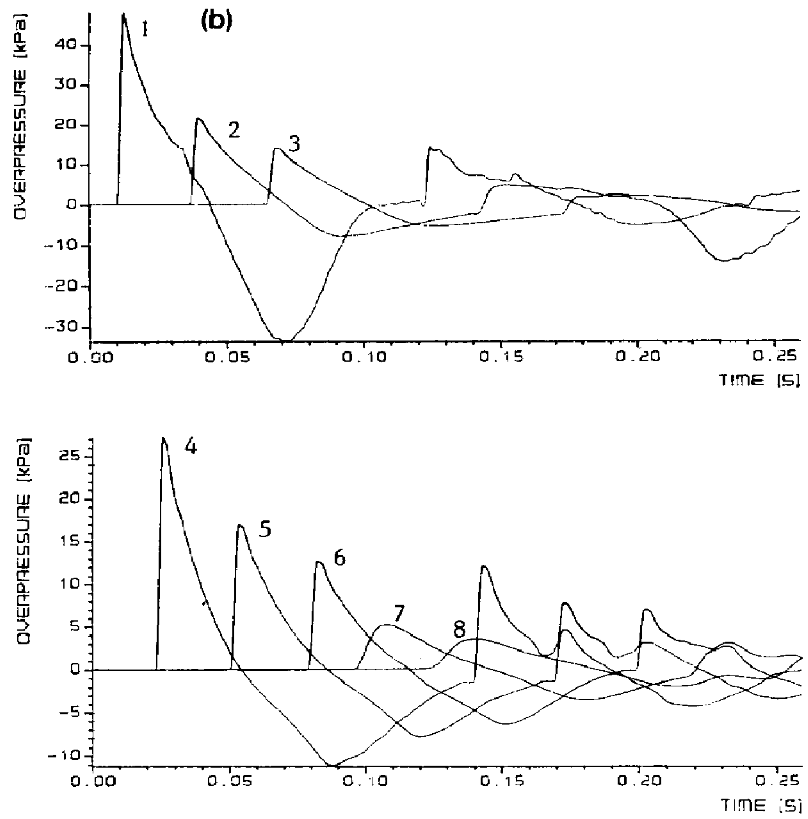
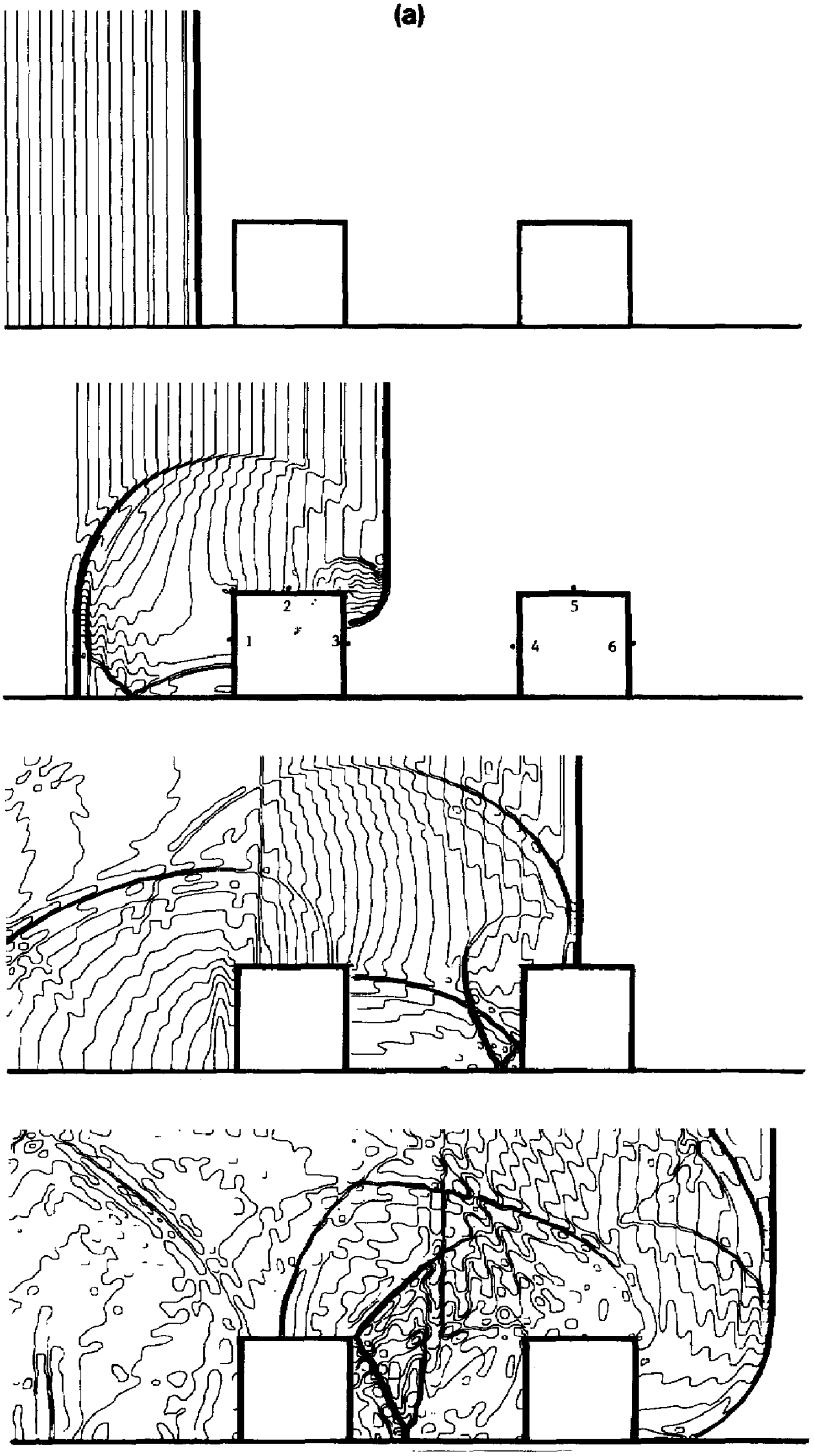


Fig. 7. Continued.

pressure distribution is visualized by a pattern of isobars, one for each change in pressure of 2.5 kPa. Shock phenomena are present where isobars accumulate. In addition, the overpressures sampled at various locations at the earth's surface as well as at the tank's wall and roof are represented in Fig. 7(b). Figures 7(a) and 7(b) show some features which are very characteristic of blast from gas explosions.

1. The blast wave shows a very pointed negative phase.
2. At the rim of the vent opening, a vortex structure is generated. Such a flow phenomenon is characterized by a substantial pressure dip in its centre.
3. The formation of a secondary wave. Blast is the result of fast expansion of combustion products. Because of the inertia of the expanding fluid, the

Fig. 8. (a) BLAST simulation of the blast wave reflection by a complex of two buildings. Pressure field visualized by an isobar pattern, one isobar for each change in pressure of 0.5 kPa. (b) Overpressures sampled in various locations in the buildings. Locations are given in Fig. 8(a).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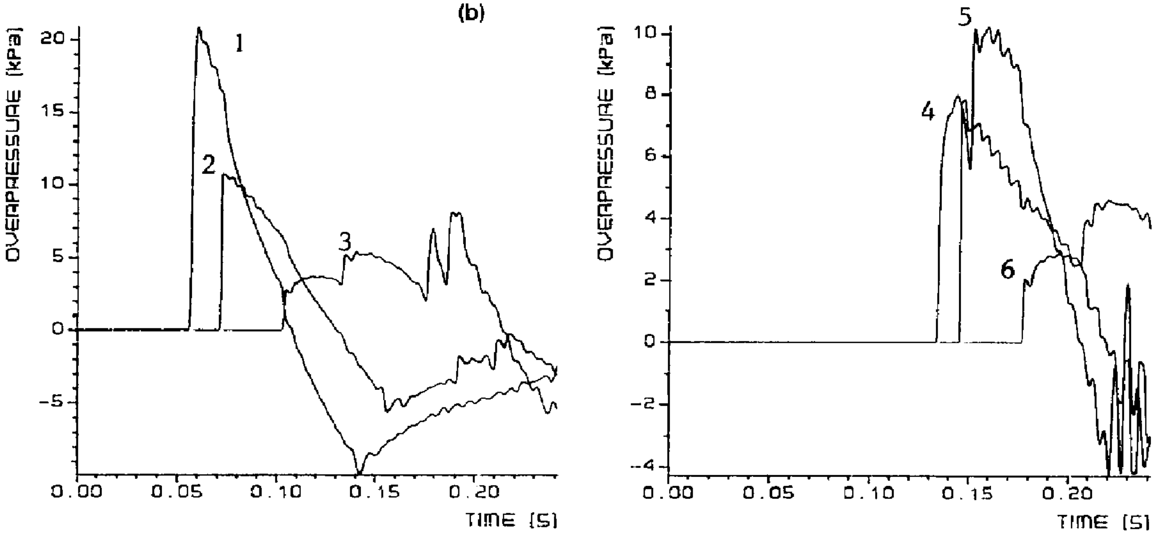

Fig. 8. Continued.

combustion products overexpand, while generating under-ambient pressures in the blast centre. Consequently, the flow reverses which results in recompression of the fluid in the blast centre. The subsequent expansion produces a secondary wave.

These phenomena come alive in the sequence of pictures in Fig. 7(a) and can be traced in the overpressure samples in Fig. 7(b).

3.7 Blast loading

Numerical simulation of blast may reveal all details of the blast loading endured by any object of any shape at any distance from the explosion. To demonstrate this, in Figs. 8(a) and 8(b) the results are presented of a BLAST [23] simulation in a 350 × 150-node grid of a blast wave of 10 kPa overpressure and 60 ms duration falling in at two buildings located close behind one another. It is to be expected that the blast loading at these buildings will be considerably influenced by one another's presence.

In Fig. 8(a) the pressure field is represented which develops as a consequence of the blast wave reflection at the configuration. At some consecutive points of time the pressure distribution is visualized by means of an isobar pattern, one isobar for each increase in pressure of 0.5 kPa. The pictures give a clear view of how the blast loading is the result of a combination of wave reflection and lateral rarefaction of reflected overpressures. In particular, they show how in between the two buildings a complicated wave pattern develops, a consequence of various reflections and wave interactions. The overpressures sampled at three different locations in each building are graphically represented in Fig. 8(b). In the overpressure transients, the complicated wave pattern can be readily recognized.

The overpressure build-up in transient number 3, for instance, sampled at the back wall of the first building shows a sequence of four shock phenomena which can be traced in the plots. The first corresponds with the passage of the shock of the infalling blast wave, diffracted around the building. The second corresponds with the same wave, after reflection by the ground.

The third corresponds with the infalling shock wave, reflected directly from the front of the second building. This shock phenomenon is immediately followed by a fourth which is the result of reflection by the second building and the ground.

The computation shows that the blast load at the front of the second building is considerably less than the reflected overpressure of the undisturbed blast wave endured by the front of the first building. In this way the effects of blast load reduction by sheltering effects can be quantified. Such calculations can provide the data required for the determination of the behaviour of structures under blast loading.

4. Conclusion

The two most current methods for vapour cloud explosion blast modelling are described and demonstrated in a simple case study. It shows that TNT-equivalency methods are easy to use. Because of the direct empirical relation between TNT and structural damage, they are particularly attractive if the vapour cloud's property damage potential is the major concern. They should only be used to determine far-field blast effects. TNT-equivalency methods, however, are unsatisfactory is several respects. In particular, they fail when the actual conditions to be modelled differ substantially from so-called "average major incident conditions", i.e. the conditions the used values for the TNT-equivalency were based on.

The multi-energy method is an alternative. Contradictory to TNT-equivalency, in the multi-energy concept, the fuel–air mixture is considered to be explosive only in partially confined, congested or obstructed areas of the cloud. In the multi-energy method, an extra parameter — the initial blast strength — is introduced which may be difficult to determine. However, even if the blast strength is conservatively estimated, the multi-energy method gives a more appropriate prediction of the explosive potential of a vapour cloud than TNT-equivalency methods. It should be emphasized that the multi-energy concept holds only if the possibility of unconfined vapour cloud detonation can be ruled out.

The multi-energy framework is a flexible concept which makes it possible to incorporate current experimental data and advanced computational techniques into the procedure of vapour cloud explosion blast modelling. In particular, the application of computational fluid dynamic codes such as REAGAS and BLAST are shown to contribute to a more and more sophisticated approach in vapour cloud explosion hazard analysis. Although the computational results presented were obtained with two-dimensional methods, three-dimensional methods are fully operational.

In the near future, substantial progress in vapour cloud explosion blast modelling can be made by:

1. The development of a data base containing data on both vapour cloud explosion incidents and gas explosion experiments (small- and full-scale).
2. A further development of software for the computational simulation of the process of turbulent premixed combustion in gas explosions and blast effects.
3. The multi-energy concept applies only if the possibility of unconfined detonation can be ruled out. Therefore, the confidence in the multi-energy method for vapour cloud explosion blast modelling will increase substantially if the conditions under which the possibility of unconfined vapour cloud detonation should be considered, are further specified.

References

1 TM5-1300, Structures to Resist the Effects of Accidental Explosions, Technical Manual, Departments of the Army, Navy and Air Force, TM5-1300/NAFVAC-P 397/AFM 88–22, 1969.

2 T. Gobert and A. Lannoy, Analyse d'accidents dans l'industrie pétrolière. Determination de l'équivalent TNT des hydrocarbures, SMIRT 4, San Francisco, CA, 1977.

3 A. Lannoy, Analyse des explosions accidentelles réelles. Evaluation du rendement d'explosion pour la prévision des effets de surpression, Revue Générale de Thermique, March, 1982.

4 A. Lannoy, Analyse des explosions air–hydrocarbure en milieu libre. Etudes déterministe et probabiliste du scénario d'accident; prévision des effets de surpression, Bulletin de la Direction des Etudes et Recherches d'Electricité de France-Série A, No. 4, Saint Denis, 1984.

5 French Authority Safety Rule, Règle fondamentale de Sureté I.2.d Prise en compte des risques liés à l'environnement industriel et aux voies de communication. Ministère de l'industrie, Paris, 1982.

6 French Chemical Industry, Cahier de sécurité: Explosion de gaz en milieu non confiné, Union des Industries Chimiques, 1986.

7 K. Gugan, Unconfined Vapour Cloud Explosions, The Institution of Chemical Engineers, London, 1979.

8 D.K. Pritchard, A review of methods for predicting blast damage from vapour cloud explosions, J. Loss Prev. Process Ind., 2(4) (1989) 187–193.

9 A.C. van den Berg, On the possibility of vapour cloud detonation, TNO Prins Maurits Laboratory Report No. PML 1987-IN-50, Rijswijk, The Netherlands, 1987.

10 D.S. Burgess and M.G. Zabetakis, Detonation of a flammable cloud following a propane pipeline break on December 9, 1970 in Port Hudson, MO, USA, U.S. Bureau of Mines Report of Investigations No. 7752, Washington, DC, 1971.

11 A.C. van den Berg, The Multi-Energy Method – a framework for vapour cloud explosion blast prediction, J. Hazardous Mater. 12 (1985) 1–10.

12 J.P. Zeeuwen, C.J.M. van Wingerden and R.M. Dauwe, Experimental investigation into the blast effect produced by unconfined vapour cloud explosions, In: 4th Int. Symp. on Loss Prevention and Safety Promotion in the Process Industries, Harrogate, UK, 1983, pp. D20–D29.

13 A.J. Harrison and J.A. Eyre, The effect of obstacle arrays on the combustion of large premixed gas/air clouds, Combustion Sci. Technol., 52 (1987) 121–137.
14 C.J.M. van Wingerden, Experimental investigation into the strength of blast waves generated by vapour cloud explosions in congested areas, In: 6th Int. Symp. on Loss Prevention and Safety Promotion in the Process Industries, Oslo, 1989, pp. 26–1/26–16.
15 A. Lannoy and A. Leroy, A practical way of assessing semi-confined explosion effects, In: 6th Int. Symp. on Loss Prevention and Safety Promotion in the Process Industries, Oslo, 1989, pp. 99–1/99–14.
16 R.J. Harris and M.J. Wickens, Understanding vapour cloud explosions — An experimental study, In: 55th Autumn Meeting of the Institution of Gas Engineers, 27–28 November, 1989, Kensington, UK.
17 J. Brossard et al., Air blast from unconfined gaseous detonations, Prog. Astronaut. Aeronaut., 94 (1984) 556–566.
18 B.H. Hjertager, Simulation of transient compressible turbulent reactive flows, Comb. Sci. Technol., 27 (1982) 159–170.
19 B.H. Hjertager, Simulation of gas explosions, Mod. Ident. Control, 10(4) (1989) 227–247.
20 A.C. van den Berg, Current research at TNO on vapour cloud explosion modelling, In: Int. Conf. on Vapour Cloud Modelling, Cambridge, MA, 1987, pp. 687–711.
21 A.C. van den Berg, REAGAS — A code for numerical simulation of reactive gas dynamics, TNO Prins Maurits Laboratory Report No. PML 1989-IN-48, Rijswijk, The Netherlands, 1989.
22 K.N.C. Bray, Turbulent flows with premixed reactants, In: Turbulent Reacting Flows, Springer-Verlag, New York, 1980.
23 A.C. van den Berg, BLAST — A code for numerical simulation of multi-dimensional blast effects, TNO Prints Maurits Laboratory Report, Rijswijk, The Netherlands, 1992.
24 E.S. Oran and J.P. Boris, Numerical Simulation of Reactive Flow, Elsevier, New York, 1987.