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EVALUATION OF VAPOUR CLOUD EXPLOSIONS BY DAMAGE ANALYSIS

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Summary

Though unconfined vapour cloud explosions can proceed in many different ways, each single one must be investigated to obtain more insight into their causes, and to increase our knowledge about the possible and probable spectrum of such incidents. Following some general remarks on the techniques and problems of damage analysis, the procedure is demonstrated by reference to an explosion in an ethylene plant in Germany in 1985.

1. Introduction

Though many precautions are taken for producing, storing and processing inflammable products, uncontrolled escape of material with subsequent ignition cannot be totally excluded. The consequence is that explosions with more or less destructive damage have occurred in the past and, unfortunately, will continue to occur in the future. Of course, every effort is taken to reduce the probability of such occurrences by increasing inherent, built-in safety by choice of material, design of the plant and care in operation and maintenance.

Especially for the design of plants the strength of pressure waves from explosions should be known in order to calculate the correct loading conditions for buildings which need to be reinforced (e.g. special control rooms). Another motivation for the assessment of damage due to explosions is the interest of insurance companies, who want to know the maximum probable loss for fixing their insurance premiums. A third reason for investigating explosion damage is the interest in modelling a specific explosion accident.

2. Theoretical consideration

To perform a damage analysis, two things have to be known.

- The relationship between a pressure wave and damage.
- An explosion model that links the pressure wave to a certain amount of hydrocarbons escaping from a leak.

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Fig. 1. Pressure-time record of a detonation wave.

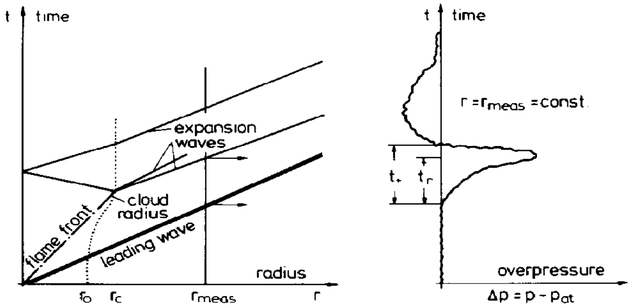

Fig. 2. Wave diagram and pressure course of a spherical deflagration.

Both points are strongly interconnected, since the form of a pressure wave depends on the nature of the explosion. From many investigations [1], it is known that a blast wave from a detonation — solid explosive, or gas detonation — has a very steep rise, followed by a nearly exponential decay, and has a negative pressure peak which is distinctly smaller than the positive one (Fig. 1). The duration of the positive phase for gas detonations of e.g. a 1 ton hemispherical mass of hydrocarbons is of the order of 40 to 80 ms (the longer time applies to large distances [2]).

The generation of pressure waves from deflagrations is different. This is explained with the aid of Fig. 2, which shows the idealized case of a spherical flame front moving with constant speed [3]. Pressure waves from the flame front, which acts like a spherical piston, are sent with the speed of sound into the surrounding air. When the edge of the cloud is reached, the spread of flame stops and expansion waves follow the compression waves. Inside the cloud a geometrically similar pressure field is established, the maximum pressure being at the flame front. Outside the cloud this pressure pulse is increasingly shortened by the expansion waves, thus cutting the peak pressure as well. The shape of the deflagration pressure wave at a fixed position is different from a detonation wave: A slow rise up to the maximum value and a rather steep decay

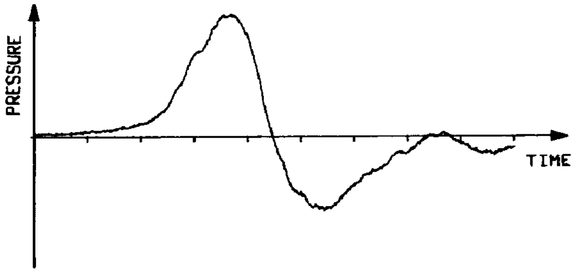

Fig. 3. Pressure wave generated by ignition of a turbulent gas jet (from [7]).

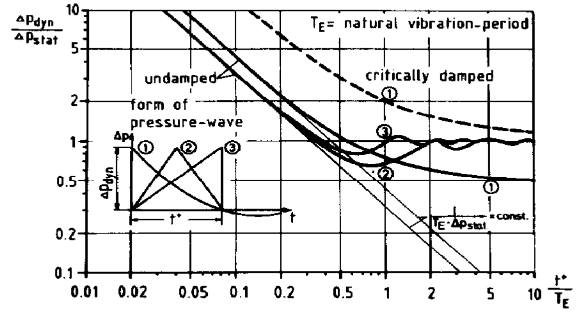

Fig. 4. Dynamic load factor for a one-dimensional oscillator (from [3]).

(Fig. 3). The peak pressure and the duration of the positive phase depend on the flame speed, this itself being a function of turbulence in the cloud, a fact discussed later. The duration of the positive phase of a deflagration wave is distinctly longer than that of a detonation wave, e.g. for a 1 ton mass of hydrocarbons and a flame speed of 100 m/s in the order of 150 ms.

If detonation or deflagration waves act upon structural elements the latter behave quite differently, as can be seen from Fig. 4, which shows the idealized case of a one-dimensional undamped oscillator system. The diagram shows the ratio of dynamic to static peak pressure for equal deflection (i.e. for equal degree of destruction) as a function of the positive duration referred to as the natural fibration period of the system. For short impulse-like loadings, the detonation wave has less energy than a deflagration wave of the same duration, the dynamic peak pressure for the same deflection may be higher. For long-time loadings the detonation wave may be only half as strong as the deflagration wave, which behaves like a static load.

3. Problems of damage analysis

With this pattern of behaviour in mind, we have to consider destruction charts, like the one shown in Fig. 5, very critically. Like the charts by Brasie

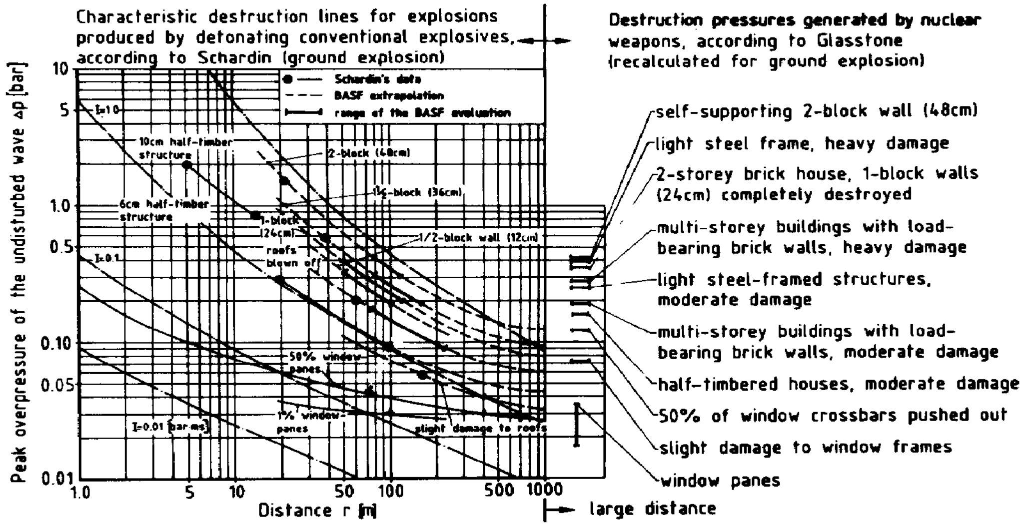

Fig. 5. Destruction curves for detonation waves.

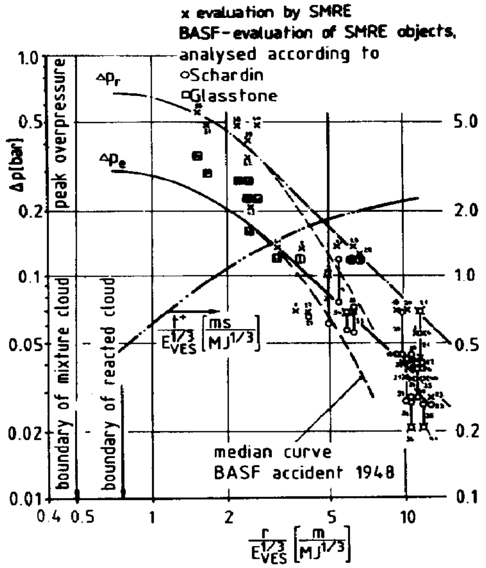

Fig. 6. Damage analysis of the Flixborough explosion (from [3]).

and Simpson, Robinson or Jarrett (references in [1] or [3], they have been established with data points from war destruction, from tests with nuclear weapons or from experiments with solid explosives, i.e. all these curves refer to blast waves from detonations. Since no results for deflagration waves are known, these or similar curves have been used in the past to investigate the

Fig. 7. Typical damage close to the 1948 vessel explosion at BASF (from [3]).

strength of unconfined vapour cloud explosions, e.g. by Sadée [4] for the Flixborough explosion or by BASF-authors [3] for two tank rupture explosions with subsequent ignition. The result of such a damage analysis is shown in Fig. 6. The destructive pressure for different objects has been plotted against the distance from the explosion centre, referred to the cube root of the energy of the hydrocarbon escaping from the vessel. These values were known very accurately in the two vessel accidents, but not quite so well in the Flixborough explosion. The destruction pressure was evaluated from photographs like that in Fig. 7, and by use of the aforementioned destruction curves (Fig. 5). In Fig. 7, the wall of the staircase was destroyed by a peak load of 0.36 bar. Since this wall was struck by a reflected wave, the pressure of the free-running wave was only 0.18 bar. As a result of the damage analysis of several accidents and of experiments on bursting tanks filled with up to 500 kg of propylene the working chart in Fig. 8 was obtained in [3]. It shows the peak overpressure as function of vessel contents and distance. It has to be pointed out once more that this result is linked to the presence of rather strong turbulence, e.g. from the expansion process of a bursting vessel or due to the obstruction by many structural elements like in Flixborough.

A second method to relate explosion pressure to the amount of hydrocarbon involved is the multi-energy method of the Dutch TNO institute [2, 8]. As can

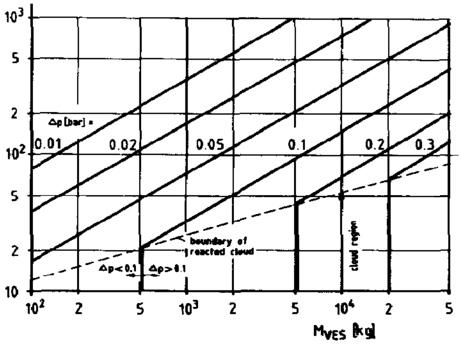

Fig. 8. Pressure of unconfined vapour cloud explosions following tank rupture (from [3]).

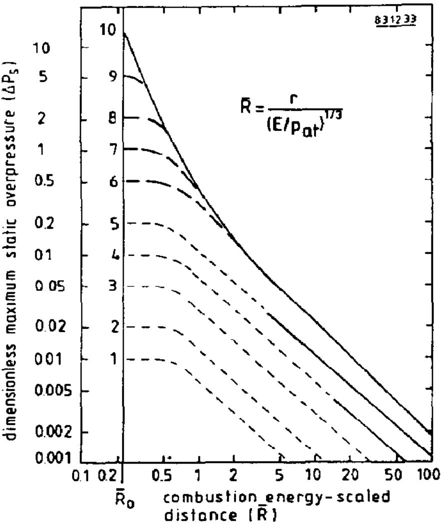

Fig. 9. Explosion pressure according to the multi-energy method of TNO (from [2]).

be seen from Fig. 9 the initial strength of the explosion, being a measure of the degree of confinement and obstruction, has to be guessed.

4. Damage analysis of the explosion at ROW

These working diagrams have been used — together with structural dynamic calculations — to investigate an explosion at the "Rheinische Olefinwerke Wesseling" (ROW) on 18th January 1985. A bypass line of 100 mm diameter for a pump in an ethylene plant had broken, the probable cause being the accumulation of vestiges of water in the unused pipe and freezing due to the low outside temperatures. Within 3 minutes, some 3 to 4 tons of hydrocarbons, mainly propylene, had escaped from the leak and spread over an area of 100×200 m. The main portion of the gas was contained in a flat cloud near the ground. The ignition probably occurred here. Some part of the gas was trapped between the platforms, pipe racks and columns, thus augmenting flame-induced turbulence. Figure 10 shows an aerial view of the plant some time after the accident, after clearing-up had already been done to some extent.

Choosing the right objects for damage analysis is problematic. First of all, we are looking for objects which can be found in a damage catalogue. In this case only glass breakage could be considered. On a second view we search for objects which have clearly been exposed to the pressure wave, be it reflected or side-on, and whose deformation can be unambiguously related to the blast load and can be assessed with reasonable effort.

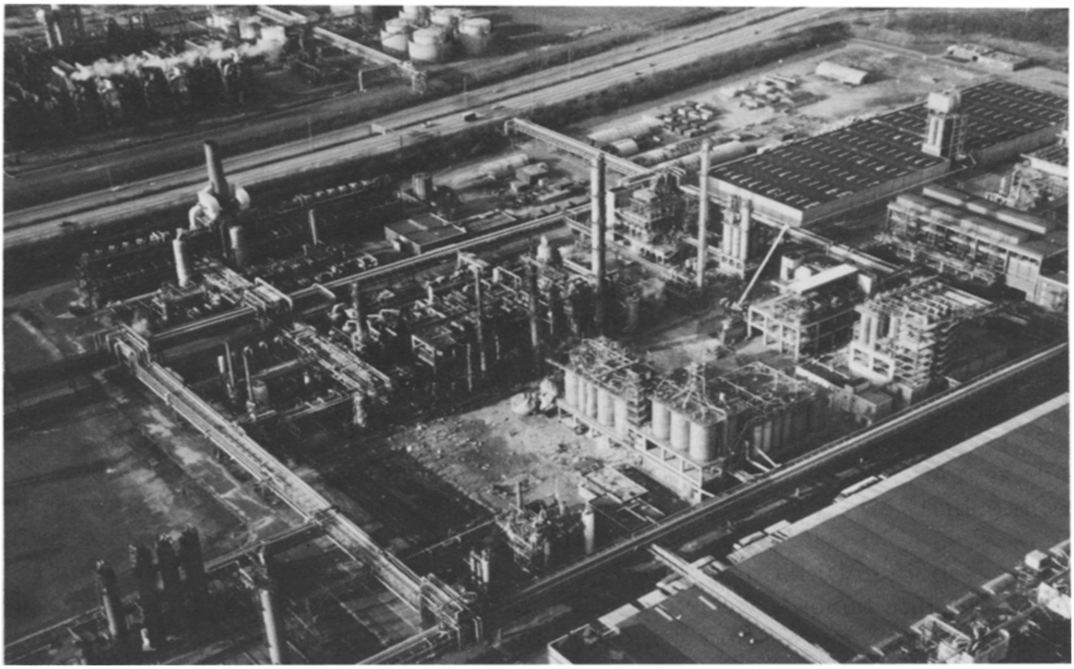

Fig. 10. Aerial view of the damaged ethylene plant at ROW.

One example of the latter case is the control room in the lower part of the picture between the large tanks and the slender white one. Knowing that the center of the explosion was between the two dark columns in the middle of the picture, we can see that the roof of the control room experienced the side-on pressure of the undisturbed wave. The roof was double-T beamed as shown in Fig. 11. From the area of the part of the roof, supported by one beam and the permanent plastic deformation of the beam, a static pressure of 57 mbar was estimated. An extensive dynamic calculation for this object yielded a peak pressure of 80 mbar for a deflagration wave with a positive phase duration of 100 ms.

Another object chosen for pressure evaluation was a pillar within the construction, supporting a densely covered pipe rack, close to the explosion centre. As can be seen from Fig. 12 this beam was lifted by the pressure acting below the rack. Again, assessing the relevant rack area and equating the force for pulling-out the anchor bolt yielded a pressure of 260 mbar.

A third type of object for pressure evaluation was a special safety window installed in several buildings close to the ethylene plant. These windows were equipped with safety glass panes covered with a thick transparent foil and having a rated breakage component in its lock. No windows were broken but several had opened. Static tests have shown that the lock ruptures at a load of

Fig. 11. Destruction in control room of adjacent plant.

62 mbar. Since the natural frequency of these lock elements is very high, they have been loaded nearly statically. In most cases the windows were struck by the reflected wave.

Like in many explosion evaluations in literature, glass breakage has been used for damage analysis. According to Pritchard [5] 50% breakage of normal window planes can be expected for pressures between 30 and 60 mbar (cf. Fig. 5). Such damage was found at a distance of 200 to 400 m from the explosion centre.

5. Comparison of observations with models

These evaluated peak pressures have been plotted against distance and compared to two deflagration models mentioned in Chapter 3. If the turbulence

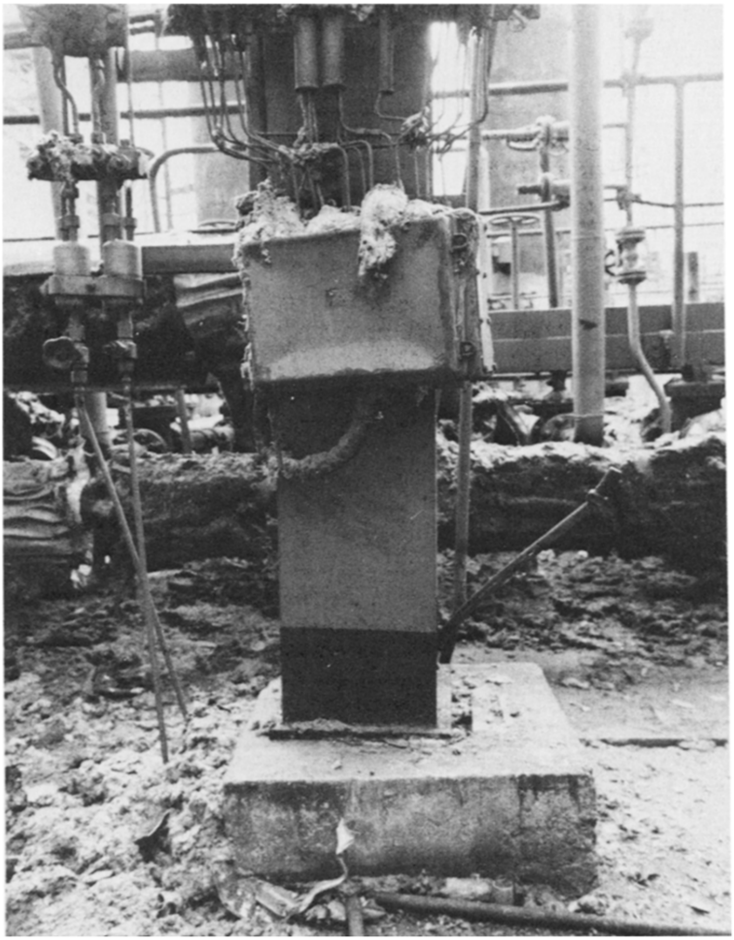

Fig. 12. Pillar with anchor bolt pulled out.

level had been similar to that following a vessel rupture, (Fig. 8) an amount of 2 to 4 tons of propylene must have been involved in this explosion (Fig. 13), a value which agrees with the assessed loss of inventory.

As mentioned in chapter 3, the initial strength of the explosion has to be guessed for the TNO method (see Fig. 9). Choosing the mean class number 5, one finds that between 0.5 and 3 tons of hydrocarbon must have been involved in this accident (Fig. 14). The choice of class 4 would yield an amount between 2 and 10 tons.

For the sake of completeness, the so-called TNT equivalent should also be mentioned. Since catalogues for damage from solid explosives are used to investigate unconfined vapour cloud explosions, it has been generally adapted to

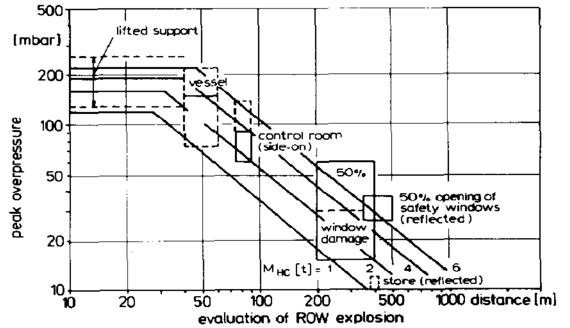

Fig. 13. Comparison of damage analysis by vessel-burst method (BASF).

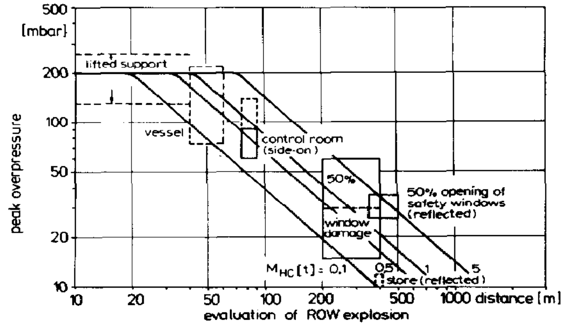

Fig. 14. Comparison of damage analysis by multi-energy method (TNO, confinement class 5).

(evaluation of 23 incidents, J. Davenport, Loss Prevention 1983)

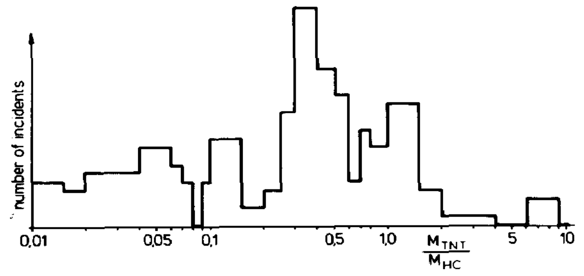

Fig. 15. TNT equivalent of unconfined vapour cloud explosions.

describe their destructive strength by an equivalent amount of TNT, a method frequently used by insurance companies. It was an insurance specialist, therefore, (Davenport [6]) who studied many past explosion accidents and assigned equivalent TNT masses to their strength, as far as possible. Figure 15 has been drawn up on the basis of his data. It shows the wide spectrum of real accidents. There is an accumulation at an equivalence of 0.4 kg TNT per 1 kg hydrocarbons.

According to this method, the Wesseling explosion had an equivalent strength of 0.2 to 1.2 tons of TNT.

8. Conclusions

Evaluation of the force of unconfined vapour cloud explosions by damage analysis cannot avoid their occurrence. It enlarges, however, the knowledge about the possible spectrum of such accidents. The explosion of the "Rheinische Olefinwerke Wesseling", Germany, in 1985 was "typical" for the following reasons. Some 4 to 5 tons of propylene had escaped from a leak, the greater part being contained in a flat cloud close to the ground. Higher pressure up to 0.2 bar was found only in the immediate neighbourhood of the more confined part of the plant section. Though the pressure decreased rapidly with increasing distance, explosions of such extent can still cause considerable glass breakage at distances up to 500 m.

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