Knowledge gained from hazard studies and accidents investigations

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KNOWLEDGE GAINED FROM HAZARD STUDIES AND ACCIDENTS INVESTIGATIONS

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ABSTRACT

In view to prevent major technological hazards according to the European Directive (82/501/EEC), hazards investigations were performed on different plants of various industries. On an other side of view, accidents investigations were also performed.

Both activities increase knowledge in order to evaluate more accurately zones that could be reached by harmful effects in case of an accident.

Considering the size of different plants of various industries, attention was paid to effects like blast over pressure, heat radiation, fragment's dispersion, and toxicity due to atmospheric dispersion of gases and vapours.

Comparisons and comments of the calculations related to the above mentioned effects using differents methods available in the literature were made.

Practical uses of the results aimed at the evaluation of the synergetic effect between individual accidents from one plant to another and at safety perimeters.

Typical accidents with some of the above effects are briefly described.

I – INTRODUCTION

According to the European Directive (1) related to the prevention of major technological hazards, in France, individual hazards investigation are generally carried out for each individual facility and, according to French regulations (2), three different reports may be issued :

– a survey of the hazards (Etude des dangers),
– an Internal Operation Programme (Plan d'Opération Interne – POI –),

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- in some cases, administrative authorities may ask a third party for a critical survey (étude de sûreté ou analyse critique de l'étude de dangers) of the hazards and related internal operation programme.

In addition, general survey of an industrial estate is sometimes required by the administrative authorities.

In the first part of this paper, acceptable pressure and heat radiation threshold values and energy threshold values for missile effect have been choosen for the scenarios of major technological hazards such as fires and explosions. The effects on the population and on the facilities are critically analysed and emphasis on energy threshold values for fragment dispersion will be given when presenting means of assessing the effects.

The four following parts will be devoted respectively to calculation means used for evaluation of the effects of pool fires, bleve and explosion (both confined and unconfined) and toxicity effects in case of release of gas and vapors to the atmosphere.

Observations drawn from the investigations of accidents will be critically reviewed (8).

A more detailed review of several of these subjects is given in publication (6).

II – PRESSURE AND HEAT RADIATION THRESHOLD VALUES AND ENERGY THRESHOLD VALUES FOR MISSILE EFFECT

II.1. Pressure effects.

II.1.1. Effects on individuals.

After a close examination of existing data, a threshold pressure value of 50 mbar was accepted for reversible pressure effects on man.

This level is consistent with the value fixed in french regulation related to safety distances in pyrotechnic plants (3) when using the pressure versus the scaled distance curves determined with trinitrotoluene detonations.

This french regulation takes also into account the threshold pressure value of 170 mbar for significant lethality.

These thresholds values are defined in terms of incident pressure. We do know this is an over–estimation for small explosions (for instance in the order of 100 kg TNT equivalent).

In fact, time has to be considered : the impulse effects have an important influence on men and facilities. For men, two types of effects are in fact to be examined :

- injuries to eardrums and lungs,
- people set in motion by the shock wave.

It is well known that eardrums do not withstand a rapid rise in pressure. Time is a parameter to be taken into account by the means of impulse. Transient effects may appear when surpression exceeds 0.15 bar, if positive impulse – I – is over 0.02 bar.ms. Eardrums may be ruptured with a surpression up to 0.35 bar and an impulse over 0.5 bar.ms.

A sudden overpressure on the thorax may easily cause pulmonary injuries. Importance of the disease is an increasing function of the ratio P/P_{atm} (overpressure/atmospheric pressure) and of the ratio $I/M^{1/3} / P_{atm}{}^{1/2}$ where M is the weight of individual.

But people may also be set in motion by the shock wave. The initial speed is function of the overpressure P and of $I/M^{1/3}$. When this speed is less than 3 m/s, there is no particular risk. By collision of the head against a part of a fixed installation, a fracture of the skull may happen when this speed is 4 m/s ; it will happen quite surely when the speed is 7 m/s and with 50 % probability when speed is 5.5 m/s. By collision of an other part of the body than the head, the corresponding values for speed are 6.4, 42 and 16.5 m/s.

II.1.2. Effects on structures.

Data are available about the behaviour of walls, structural equipment and window panes (19). Structural equipment design may include layout and devices to limit explosion damage. Nevertheless the analyst has to bear in mind the synergetic effects a blast wave may produce on the surrounding equipments. Only few informations is available for instance in an existing plant, the main difficulty lying in the lack of data for previous designs.

With regard to the pressure effect on facilities, TNT curves (4) give the incident peak overpressures versus scaled distances. But the effects of reflections are to be considered ; these curves are consistent for explosives and mainly in the far fields. For detonation of gases (5), evaluation tests are summarized on figure 1.

Currently, only scattered results are known (5) and experimental investigations to validate physical models mainly considering deflagrations in unconfined explosions and accidental missiles projection are needed.

II.2. <u>Heat radiation threshold values from fires and BLEVE</u>

II.2.1. Effects on individuals.

For the survey of hazards the following threshold values for heat radiation are generally considered when the duration of the fire is quite high (more than 60 s) :

– 5 kW/m² for severe casualties and lethality,

– 3 kW/m² under this threshold, the radiation effect on man is reversible.

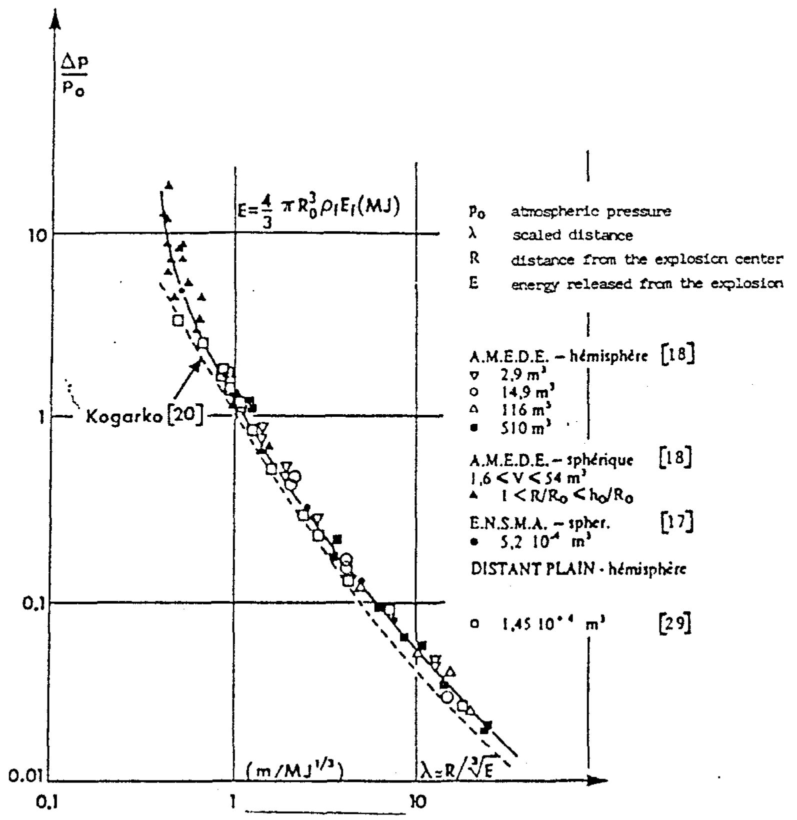

Figure 1 : Detonation peak overpressure of unconfined air–hydrocarbon mixtures (spherical geometry) [from A. Lannoy (5)]

These threshold values are to be used only when men are unable to escape and run away from heat effects.

Nevertheless, when people is properly drilled, higher values could be accepted (for instance : 8 kW/m² for firemen with suitable equipment and a quite short stay).

For long duration effects, it is possible to quote correlations giving the threshold values of injury (at a low probability) and lethality as a function of time (9).

In the case of BLEVE, the duration of the phenomenon is very short : it can be currently assessed that the duration is in the order of 20–30 s for spheres containing 500 m³ to 1500 m³ of liquefied gas. So, higher threshold values for heat radiation than those for high duration fires could be used.

For 1 % fatality level, the threshold flux : $\phi = 190.81\ t^{-0.771}$
(ϕ kW/m² and t s) is given on figure 2 according to EISENBERG values quoted by MUDAN (9)

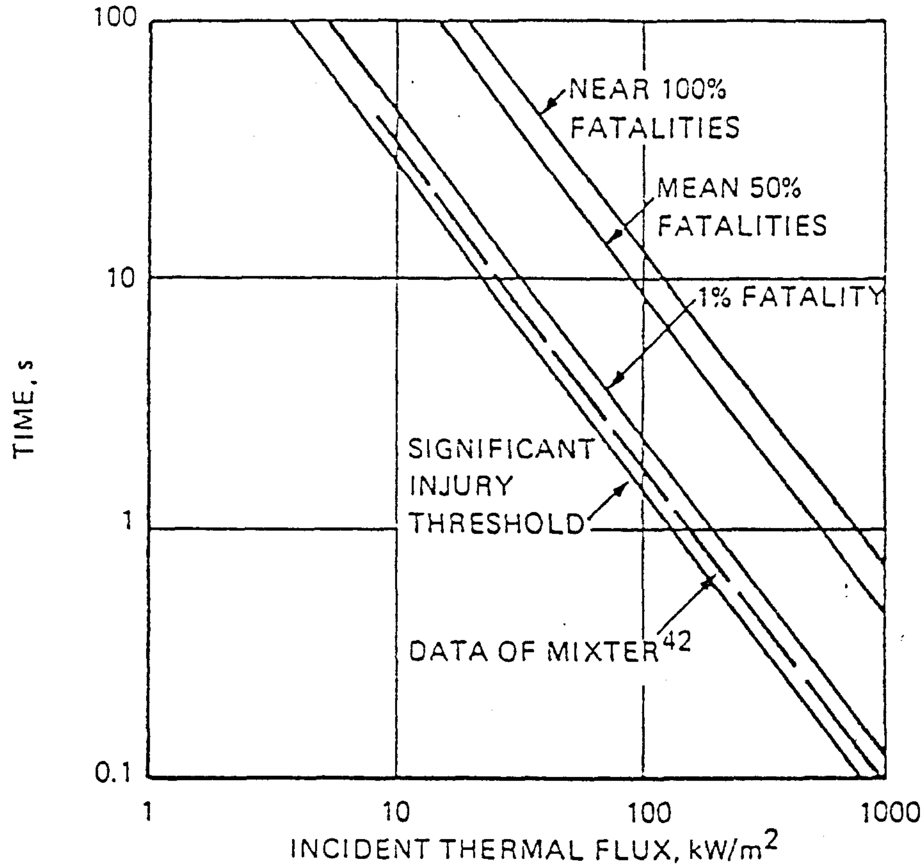

Figure 2 : Fatality levels for thermal radiation (Eisenberg and al.[43]) [From MUDAN (9)]

II.2.2. Effects on facilities.

With regard to the heat radiation effects on facilities, various cases are to be taken into account. Thus, threshold values cannot be easily and univocally given. Many calculations are possible when the behaviour of the material in presence of fire is known.

These considerations are global and, for example LANNOY (10) deals with heat conduction in concrete. But spacing distances derived from thermal radiation models are also needed. They are for instance given by CROCKER and NAPIER (11) in table 1.

II.3. Explosion energy threshold values for missile effect.

II.3.1. Energy threshold values.

For individuals, the only important energy threshold values for missiles effect is the one corresponding to lethality. It is not worth worrying about defining a reversibility threshold for when a missile penetrates any part of the body.

FUEL	TANK DIAMETER (m)					*S/D Average	RANGE of S/D
Solid Flame Model (+ Morgan/Hamilton V.F.)							
	_10_	_20_	_30_	_40_	_50_		
Benzène	11	21	32	40	49	1.04	1.1–0.9
Gasoline	10.1	19	28	36	43.5	0.93	1.0–0.9
Hexane	5.6	11	16	21	26	0.54	0.6–0.5
Ethanol	8.5	15.3	21.6	27.5	33	0.74	0.9–0.7
Equivalent Radiator Model (Vertical target) (22)							
Benzène	9.5	18	25.4	32.4	39	0.86	1.0–0.8
Gasoline	8.4	15.2	21.3	27	32	0.73	0.8–0.6
Hexane	4.0	7.5	10.6	13.5	16	0.36	0.4–0.3
Ethanol	6	10	15	16	18	0.47	0.6–3.2

* (S/D) is the ratio tank spacing/diameter

Table 1 : Recommended tank spacings (S) based on 37.8 $kW.m^{-2}$ incident radiation [THOMAS (5) L/D correlation]

The french pyrotechnic regulation gives this lethality threshold value as equal to 20 Joules. This value is connected to the boundary between a zone defined by "serious and maybe lethal injuries" and a zone defined by "injuries".

When an explosion occurs, the impulse $\int p.dt$ which sets the fragments in motion is of paramount influence.

In industry, most accidental explosions experience proved that the mean weight of a fragment is of the order of 30 to 100 kg. When the fragment has a 10–15 kg weight and a 4 m/s speed, its kinetic energy is 80–120 Joules. Thus we have choosen an energy threshold value equal to 100 Joules.

II.3.2. Missile effects.

For the prediction of the missile effet during accidental explosions, simple calculation methods were defined in TNO yellow book (18). They were completed in the UCSIP (Union des Chambres Syndicales de l'Industrie du Pétrole) guide for hazard evaluation in the petroleum industry (17).

This approach can be summarized in the three following steps :

- energetic calculation of the initial speed of a fragment,
- ballistic calculation with possible consideration of a drag coefficient,
- comparison of the ballistic results to lethal energy threshold values for individuals and to impact perforation speeds for pieces of equipement.

Even though complex softwares have been developped, the mechanisms of bursting for different types of material and vessel shapes was only validated until now for simple configurations and mainly metallic materials under dynamic loading from an explosion.

Therefore the first main difficulty is to define the bursting pressure of the enclosure, the location where the initial breaking occurs and the number and shapes of the missiles. Then during the projection, the direction is strongly dependent on pressure history and the shape and mass of the missiles.

But, for apparatus of complex shapes and buildings, directional effects and the exact location of the weakest part of the system combined with the propagation mechanism of the explosion imply great uncertainties about the maximum landing distance for the missile and its random distribution.

Therefore, comparisons of results gained by investigating accidental explosions and by simple calculations are needed for prevision purposes in hazard studies (see V).

III. POOL FIRES.

The main purpose is to assess the radius of the effect (r). Burning rate, flame height, amount of heat radiated from the fire are important parameters.

For LPG (Liquefied Petroleum Gases), we have considered an emissive power of 60 kW/m^2 according to MIZNER and EYRE (16) (to be compared to 30 kW/m^2 for liquid hydrocarbons).

From this thermal radiated flux one can calculate the flux received considering view factor and attenuation through air can be calculated. The table 2 gives calculations of the radii for different heat radiation threshold values with 20 and 30 m long square pools.

These calculations are conservative and other parameters such as the geometry of the dyke, screen effect of construction, view factors are to be taken into account if more accuracy is needed.

The influence of the wind could be also of paramount importance leading to the tilt and the drag of the flame.

Then, the radiative effect may be calculated from a tilted cylinder in the wind direction. The area involved takes an elliptical shape. Even, the longest dimension is only 25 % higher than the previously calculated radius. But, the convective effect may become predominant.

Substance	r (m) 5 kW/m²	r (m) 3 kW/m²	r (m) 5 kW/m²	r (m) 3 kW/m²
	20 m long square pool		30 m long square pool	
LPG	58	76	80	104
Liquid hydrocarbons	35	47	48	65

Table 2 – Radius (r in meters) from the edge of the pool at different heat radiation threshold values

Nevertheless, the tilting angle and the flame length are useful to determine the pieces of equipment engulfed in fires.

IV – BLEVE.

This phenomenon, by its thermal effects, can trigger the most important major technological hazards. Comparisons between thermal and pressure effects are given.

For example, for propane or butane spheres (the volume of which range from 500 to 1500 m^3) the following calculations can be made.

IV.1. Thermal effects of Bleve.

Differents means for assessing the duration or the diameter of the fire ball and its radiation have been developped by different authors such as : NAZARIO (14), UCSIP (17), BAKER and al. (4), TNO (18)

For example, TNO (18) proposes to calculate the duration of the fire ball and its radius using the formula :

duration (seconds) t	$0.852\ M^{0.26}$
radius (m)	$3.24\ M^{0.325}$
M (kg)	is the content of the vessel

Assuming the heat radiation on the surface of the ball is 200 kW/m², and using the threshold curves reported by K.S MUDAN (9) about fatality levels for thermal radiation, it is possible to calculate :

radius (m) for 1 % lethality	$3.12\ M^{0.425}$
radius (m) for significant burns	$4.71\ M^{0.407}$

These radii are calculated at ground level, without attenuation by air.

For a 1500 m^3 butane sphere, the radius for 1 % lethality is 982 m and 1162 m for significant burns.

We have considered the existing empirical correlations giving the radius and the duration of the fire ball and its radiation and compared these calculations.

When comparing these results, we found large discrepancies (mainly related to the values of emissive powers, the position of the fireball, the attenuation by air).

IV.2. Pressure effects of the Bleve.

According to TNO Yellow Book (18) the peak overpressure of a shock wave with adiabatic flash for hydrocarbons is related to the scaled distance $r/(2M)^{0.33}$ with the parameter "superheating" (liquid temperature of the content of the vessel just before bursting open –the atmospheric boiling point of the liquid).

For example, assuming an overheating of 150 K, it is possible to calculate the radii for pressure threshold of 50 mbar.

In this case, the radius (m) for reversible wounds (pressure threshold value = 50 mbar) = 8.70 $(m)^{1/3}$.

For a 1500 m^3 butane sphere, the radius for significant burns, given in the above mentioned table, is 1162 m while the radius for reversible injuries (pressure threshold value 50 mbar), calculated by the above formula is 792 m.

It can be concluded that for injuries the pressure effects radii are lower than those for heat radiation. Consequently, for the protection of the population, (if we do not consider the missile effects), one need to consider mainly the radiation effects. But it might be pointed out that, until now, the delay of occurence of a BLEVE is quite unpredictable.

V – CONFINED AND UNCONFINED EXPLOSIONS.

Accidental explosions may be either confined or unconfined with hazardous substances as diverse as explosives, propellants, fertilizers, combustible gases and vapors and inflammable dusts.

With gases and vapors, DAVENPORT (12) pointed out that only a small part of the released gas is generally involved in the unconfined explosion.

Such an explosion occured some years ago in France in a chemical plant after the accidental release from a vessel under 40 bar pressure : 160 kg of a mixture of H_2–CH_4 were released, after the breakage of a connecting duct. In this particular case, from the effect given by the blast wave and the mechanical damages it may be concluded that only 1 kg of the H_2–CH_4 mixture released was involved in the explosion. After close examination of the mechanical damages, the TNT equivalent could be estimated at 5 kg.

INERIS established a code describing the variation with time of the dimensions of the inflammable cloud and validated it by testing the horizontal discharge in air of a vessel pressurized with H_2 or CH_4 (13).

In the survey of the hazards for assuming the maximum effects of the explosion, the time lag at which the inititation of the explosion occurred is as important as the source location in order to define the safety distances. Unfortunately, few codes can describe the generation of a cloud, particularly when it results from the discharge in air of a vessel pressurized by an inflammable gas.

Some recent accidents in France in a gasoline storage plant (St Herblain 1991), in a refinery (La Mède, nov. 1992) and in a LPG storage plant in USA (Brenham 1992) emphasized the need to develop more convenient models to deal with such unconfined explosions.

The European programme MERGE (Modelling Experimental Research into Gas Explosion) deals with modelisation and experimental validation on unconfined explosions of inflammables atmospheres.

The explosion can be semi–confined, as in 1986 in a casting line, where a very violent aluminium explosion occured causing the death of 4 people, injuring 25 others and with extensive material damage.

This explosion triggered by a thunderbolt involved the vaporisation and atomisation process of liquid aluminum. The resulting vapors and droplets, mixed with air ignited by the thunderbolt gave an explosion of and above the casting line (ground level). Then, a second explosion, not as powerful as the first one was initiated in the casting pit by the action of liquid aluminium on water. By examination of the damages to the casting pit and to the surrounding buildings, evidence was gained that the TNT equivalent was about 200 kg and 100 kg respectively for the first and second explosions. Pieces of equipment of the casting line were thrown up to 700 m (15).

Every year, a lot of accidental confined dust explosions occur in elevator buildings and silos. Damages can be more or less extensive but in some cases, when the confinement is important, with rather resistant concrete buildings, concrete missiles are thrown. In 1982 a barley and malt dust explosion occurred in Metz, France and induced the collapse of 9 out of 14 concrete cells (as a consequence of the fact that there was quite no links between the cells –independent cells–). A violent explosion in the work tower resulted in a shock wave with the projection of lightweight panels blown in a verydirectional area (no more than 100 m). The dispersion of very important concrete blocks was not larger than 80 m corresponding to the maximal height of the elevator.

The same year, another explosion was initiated in the upper part of a sugar storage plant (2 x 20000 t cells and 1 x 40000 t cell).

The two 20000 t cells were covered with an expanded concrete roof and during the explosion, quite small pieces were thrown up to a distance of 500 m, but the vertical walls remained standing even though some crevices appeared. For the largest cell (40000 t) the reinforced concrete roof first was raised up with some dismantling in large pieces but then fell again into the silo cell.

With these examples of explosions, it became evident that there is a lack of validated methods to predict the effects of such accidents. Efforts must be devoted to validating the existing models or to improving them.

VI - TOXICITY EFFECTS IN CASE OR RELEASE OF GASES OR VAPORS TO THE ATMOSPHERE.

An accident on a pipe or on a tank containing compressed or liquefied gas, a fire with chemicals may result in releases of gases or vapors mists or soots and dusts to the atmosphere. In a fire the decomposition speed of the products and the nature of toxic emissions issued must be defined (7), but will not deal with the topic of the present paper.

To evaluate the consequences of a release, in terms of effects zones, parameters about the release (source term, dispersion conditions) and about the effects on human being have to be identified.

With regard to the source term, from tanks or pipes, the release may be continuous (permanent if flow rate is not limited in time) or instantaneous depending on the type of rupture : for example fissuration in a tank or total rupture of this tank. The source term is also influenced by the physical state of the content before release.

The dispersion conditions of the toxic cloud depend on the atmospheric conditions (stability, temperature, windspeed ...) and on the site conditions (roughness ...). The phenomenon has to be studied under unfavourable atmospheric conditions.

For effects on human being, when some people inhales an atmosphere polluted by toxic components, the effects usually studied are the occurence of lethality (with low probability), the occurence of faint, of cough ...

For people exposed to such atmosphere, these effects are function of concentration (C) and time of exposure (t).

For a constant effect E, a relation ship between concentration and time can nearly be found : $E = C^n \times t$.

Where C is the concentration step
t is the time of application of C
n is a constant depending on the component
The effect E will occur if $E \geq C^n \times t$.

Thus, it is important to be able to calculate concentration field issued from the release and also to determine the history of concentration at each given point downwind the point of emission.

In case of a permanent release, the zone to be considered for a given effect is the same as the zone where the concentration is equal or above a given concentration. For this type of release, this is due to the fact that concentration versus time begins to increase and then remains constant when the system is established.

In case of an instantaneous release, concentration versus time is not constant, and the concept of equivalent dose defined above has to be considered.

Probit equations giving values for C, n, t are proposed to be used when the concept of equivalent dose is retained. The approach is very attractive but, depending on the n value choice, important deviations can be introduced in the distances calculated. On an other point of view, for the effects on human being, care has to be taken for the validity of the data, especially in case of correlations with results from experiments on animals.

At last, number of dispersion models have been computerized, but all of them have limitations and need care for their use in given applications.

VII - CONCLUSIONS

The critical analysis of hazards studies and accidents connected to pool fires, BLEVE and confined and unconfined explosions pointed out many lacks of information to evaluate the pressure, heat and missile effects.

The acceptable pressure and heat radiation threshold values and the energy threshold values for missile effects are generally based on experience gained after accident investigation or intentional experimental explosions.

The effects on individuals and facilities are both to be considered separately.

For pressure threshold values, the effects on human beings are quite well understood ; but for facilities, only scattered data are available.

Heat radiation threshold values are to be choosen differently whether BLEVE or large pool fires are involved.

For the maximum landing distances of missiles energetic and simple ballistic calculation can give an order of magnitude for bursting of vessels. In other cases only results gained from accident investigations are useful.

Calculation means for pool fires are consistent to evaluate the heat radiated from LPG (Liquefied Petroleum Gases) and liquid hydrocarbons fires. The effect of convection needs more consideration.

For BLEVE, current calculations are sufficient for predictive purposes but the delay of occurrence is rather unpredictable.

For toxicity effects, number of computerized calculation models can be found, but their use often need to be supervised by a specialist.

More experimental investigations for both confined and unconfined explosions are needed to get a better understanding of the mechanisms of the explosion, and of the behavior of equipment and buildings under dynamic loads given by these explosions.

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