Learning from Critical Analysis of Hazard Studies and from Accidents in France

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I./ INTRODUCTION.

According to the European Directive (1) related to the prevention of major technological hazards, a lot of individual hazards investigations were performed for oil, liquefied gas, chemicals, grain, fertilizers plants and storages.

Individual hazards investigation are generally carried out for each individual facility and, according to French regulations (2), three different reports might be issued :

- a survey of the hazards (Etude des dangers) to emphasize the main hazards in the facility and preventive and protective measures,
- an Internal operation Programme (Plan d'Opération Interne - POI -) with the aim of organizing fire fighting and other safety measures,
- 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 issued under the responsibility of the plant's owner.

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

The authors were personnally involved in some of these individual and general actions as well as in accident investigations.

In the first part of this paper, acceptable pressure and heat radiation thresholds and energy thresholds 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 thresholds for fragment dispersion will be given when presenting means of assessing the effects.

The three following parts will be devoted respectively to calculation means used for evaluation of the effects of pool fires, bleve and explosions (both confined and unconfined). Observations drawn from the investigations of accidents will be critically reviewed.

International Conference and Workshop on Modeling and Mitigating Consequences of Accident Release of Hazardous Materials, Hartford, 20-24 mai 1991, pp. 563-84.

II./ PRESSURE AND HEAT RADIATION THRESHOLDS AND ENERGY THRESHOLDS FOR MISSILE EFFECT.

II.1. Pressure effects.

II.1.1. Effects on individuals.

After a close examination of existing data the following threshold values for human being were accepted :

- 170 mbar, threshold for a significant lethality,
- 50 mbar, under this threshold, pressure effects on man are reversible.

The levels are consistent with the values 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 as exemplified in table 1.

Table 1

Zone	Z1	Z2	Z3	Z4	Z5
Definition given in regulation	Lethal injuries in more 50 % cases	Serious injuries may be lethal	Injuries	Possible injuries	Very little probability of slight injuries
Threshold values of scaled distances $\lambda = r/m^{1/3}$	5	8	15	22	
CERCHAR definition	Significant lethality		Injuries		Reversible effects

r (m) : radius from the center of the explosion
m(kg) : weight of TNT involved

These thresholds values are defined in terms of incident pressure. We do know this is an over-estimation for small explosions (for instance 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 0.015 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.

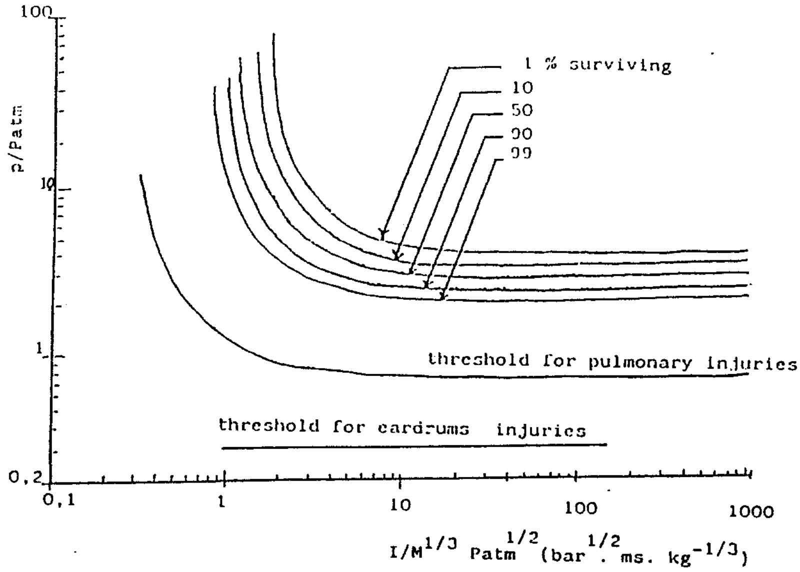


Figure 1 : Physiological effects of pressure (private communication)

A sudden overpressure on the thorax may easily cause pulmonary injuries. Importance of the disease is an increasing function of the ratio P/Patm (overpressure/atmopheric pressure) and of the ratio $I/M^{1/3}$ $Patm^{1/2}$ as exemplified on figure 1 where I is the positive impulse and M the weight of the 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 (23). 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 avalable for instance in an existing plant, the main difficulty lying in the lack of data for previous designs.

As regards 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 2.

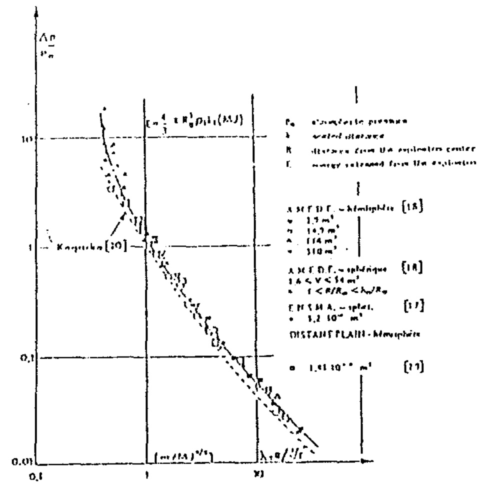


Figure 2 : Detonation peak overpressure of unconfined air-hydrocarbon mixtures (spherical geometry) [from A. Lannoy (5)]

Two extreme cases are possible :

- unconfined explosions are mostly deflagrations the flame speeds of which are mainly variable in relationship with ignition sources (6) and geometry of the confinement. However, in some cases, transition from deflagration to detonation may occur (7) (8),
- bursting of vessels in relationship with production of missiles.

Currently, only scattered results are known (5) and experimental investigations to validate physical models are needed.

II.2. Heat radiation thresholds from fires and bleve.

II.2.1. Effect on individuals.

For the survey of hazards the following thresholds are generally considered when the duration of the fire is quite high (more than 60 s). :

- 0.52 W/cm^2, for severe casualties and lethality,
- 0.29 W/cm^2, under this threshold, the radiation effect on man is reversible.

These thresholds 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 : 0.8 W/cm^2 for firemen with suitable equipment and a quite short stay).

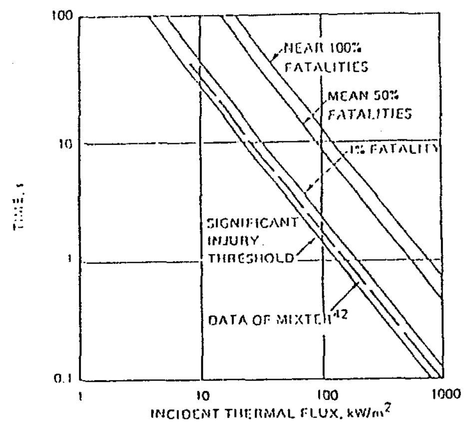
For long duration effects, it is possible to quote correlations giving the threshold value of injury (at a low probability) and lethality as a function of time (9).

In the case of Bleve, the phenomenon is very quick and higher threshold values, function of time, are thus to be used. For 1 % fatality level, the threshold flux :

$$\emptyset = 190.81\ t^{-0.771}$$

($\emptyset$ kW/m^2 and t s) is given on figure 3 according to EISENBERG values quoted by MUDAN (9). Currently, one may assess that the duration of a Bleve is in the order of 20-30s for spheres containing 500 m^3 to 1500 m^3 of liquefied gas.

Sometimes, this threshold is presented in term of dose (joules). It must be said, that in this case, this flux Ø and time t are connected by the following formula (Ø * t = constant) but this relation is no more valid when t is higher than 10 s.



Fatality levels for thermal radiation (Eisenberg et al.)

Figure 3 [From MUDAN (9)]

II.2.2. Effects on facilities.

As regards 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. 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 2.

Table 2

Recommended tank spacings (S)
based on 37.8 kWm^{-2} incident radiation
(Thomas (5) L/D correlation)

FUEL	TANK DIAMETER (m)					(S/D)* Average	RANGE OF S/D
Solid Flame Model (+ Morgan/Hamilton V.F.)							
	10	20	30	40	50		
Benzene	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)							
Benzene	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

These considerations are global and do not involve problems to which the analyst has to pay attention. For instance, the investigation of accidents led to conclude that synergetic effects have to be considered. In a given case study, a small open fire in a drain cut off a number of process sensors with major consequences for the plant.

II.3. Explosion energy thresholds for missile effect.

II.3.1. Energy thresholds.

For individuals, the only important energy threshold for missiles effect is the one corresponding to lethality. It is no worth worrying about defining a reversibility threshold for when a missile penetrates any part of the body.

The french pyrotechnic regulation gives this lethality threshold as equal to 20 Joules. This value is connected to the boundary between zone Z_2 (defined by "serious and may be lethal injuries") and zone Z_3 (defined by "injuries") (see table 1).

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

One has to bear in mind two different approaches :

- the first one related to "small fragments". In this case, the spatial distribution is of first importance and the question to deal with is about possible penetration in the human body,

- the second pertaining to "important fragments" where the penetration does not matter, but where the importance is given to injuries by percussion of the skull. The skull may be fractured (at a low probability level) when hit by a missile the speed of which is greater than 4 m/s.

The first of these approaches is valid for some ammunitions. In industry, for the vast majority of 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 cinetic energy is 80-120 Joules. Thus we have choosen an energy threshold equal to 100 Joules.

II.3.2. Missile effects.

For the prediction of the missile effect 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 thresholds for individuals and to impact perforation speeds for pieces of equipment.

Even though, complex softwares have been developped ; until now the mechanisms of bursting for different types of material and vessel shapes was only validated 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 vessel, 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 the shape and mass of the missiles.

Keeping in mind all these remarks, the following formulas are applied to the missile :

- for the initial speed VMIS (m/s) with a fragile rupture of a vessel of volume V (m3) and mass M under a pressure P (pascal),

$$VMIS = 0.97 \left[\frac{\Delta PV}{M}\right]^{0.5}$$

- for the maximum height Z_1 (m)

$$Z_1 = VMIS^2 \sin^2\alpha/2g$$ (with α angle for the projection)

- for the landing distance from the vessel (m)

$$x_2 = VMIS^2 \sin^2 \alpha/g$$

These last two formulas do not consider the drag coefficients and some results for different vessel volumes under 3×10^4 pascal pressure with the assumption of $\alpha = 45$ are given for a mass of the missile of 100 kg in table 3.

The influence of the drag coefficient DRAG = k $a/M^{1/3}$ on landing distance x_2 (k : empirical constant : 0.0014 m^{-1} $kg^{-1/3}$ for a subsonic missile with a between 1.5 and 2) is emphasized on last column of table 3 for x_2 Drag.

Table 3

V (m^3)	VMIS (m/s)	Z_1 (m)	x_2 (m)	x_2* (m)
1630	35.6	32	129	138
2900	36.5	34	136	144
3650	38.2	37	149	156
4500	38.8	38	154	161
6530	39.7	40	161	166
11600	40.5	42	167	173
14570	40.6	42	168	174
57600	43.5	48	192	198,6

x_2 is calculated assuming the missile is ejected from ground level

* x_2 drag is calculated assuming the missile is ejected from the top of the vessel

Such assumptions are consistent with observations made for example in San Juan Ixhuatepec accident (15).

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, we have more confidence about the results gained by investigating accidental explosions and simple calculations are sufficient for prevision purposes in hazard studies (see V.2).

III./ POOL FIRES.

The main purpose is to assess the radius of the effect (r). For this, three parameters are successively calculated : burning rate, flame height, amount of heat radiated from the fire.

III.1. Burning rate.

The burning rate values are either published in the literature (22) or calculated using correlations. The first of them is given by Burgess and Zabetakis :

$$\dot{y}_{max} = 1.27 \times 10^{-6} \frac{\Delta Hc}{\Delta Hv} \quad (m/s)$$

where y_{max} is the rate at which the liquid pool level decreases with time in the absence of external supply. ΔH_c and ΔH_v are respectively the net heat of combustion and the heat of vaporization (in J/kg) at the boiling point of the liquid fuel. For usual liquid hydrocarbons $\dot{y}_{max}$ is in the range 2-4 mm/min.

Then, the burning rate $\dot{m}$ ($kg/m^2.s$) may be written :

$$\dot{m} = \dot{y}\rho$$

with (kg/m^3) specific mass of the fuel.

According to Mudan (9) this way of assessing the mass burning rate underestimates the value for liquefied gases by almost a factor of two. In this case, the correlation for the mass burning rate may be preferably written :

$$m'' = 10^{-3} \frac{\Delta Hc}{\Delta Hv^*} \quad (kg/m^2.s)$$

$$\text{where } \Delta H_v^* = \Delta H_v + \int_{T_o}^{T_b} C_p (T)\, dt$$

if the boiling temperature is under the ambient, one has to consider $\Delta H_v^* = \Delta H_v$.

For LPG, theorical assumptions and experiments led to the value $\dot{m}'' = 0.11\ kg/m^2.s$.

III.2. Flame height.

The flame height - h - is calculated using Thomas's formula with equivalent diameter or the correlation given by HESKESTAD (12) for a $C_\alpha H_\beta O_\gamma$ molecule. THOMAS gives :

$$h/D = 42 \left(\frac{\dot{m}''}{\rho\sqrt{gD}}\right)^{0.61}$$

ρ : specific mass of air (kg/m^3)
D : equivalent diameter (m)
g : acceleration of gravity (m/s^2)
$\dot{m}''$: as previously defined ($kg/m^2.s$)

III.3. Heat radiated from the fire.

For LPG, we have considered an emissive power of 60 kW/m^2 according to MIZNER and EYRE (22) 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. The table 4 gives calculations of the radii for different heat radiation thresholds with 20 and 30 m long square pools.

As previously mentioned these first type 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.

Table 4

Radius from the edge of the pool at
different heat radiation thresholds - L - (m)

Substance	- L - (m) 0.52 W/cm^2	- L - (m) 0.29 W/cm^2	- L - (m) 0.52 W/cm^2	- L - (m) 0.29 W/cm^2
	20 m long square pool		30 m long square pool	
LPG	58	76	80	104
Liquid hydrocarbons	35	47	48	65

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.

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 examples, 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.

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

According to NAZARIO (14) the duration of the fire ball in seconds is calculated by :

$$t = 0.45.M^{0.333}$$

Where M (kg) is the quantity of LPG in the fire ball typically taken as the maximum content of the vessel.

The radiation from the fire ball can be estimated by :

$$qf = (0.176.R.\ LHV.\ M^{2/3}) / L^2$$

where :

: qf is in W/m^2

: R is the radiative fraction of combustion energy taken as 0.3 if the bursting pressure is less than the set pressure of the pressure relief valve or 0.4 if the bursting pressure is greater than the pressure relief valve set point

: LHV is the net heat of combustion for the material (J/kg)

: L (m) is the distance from the center of the fireball

: M (kg) is the content of the vessel

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) as previously defined

Assuming the heat radiation on the surface of the ball is 200 kW/m^2, 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. It would be possible to consider the height the ball reaches in the atmosphere. According to LIHOU and MAUND (16) this height is equal to 10t*. In fact, the correction it introduces is included in these oversimplified hypotheses, the main unknown data being the heat radiation on the surface of the ball.

According to UCSIP (17), the radius of the fireball may be calculated by :

radius (m) of the fire ball = 2 $M^{1/3}$

radius (m) for lethality = 7.182 $M^{1/3}$

radius (m) for significant burns = 10.157 $M^{1/3}$

BAKER, COX, WESTINE, KULESZ and STREHLOW (4) have developped a means of assessing the diameter and the duration of the fireball, using adimensional numbers :

diameter (m) of the fireball = 3.86 x 1.387 x $M^{0.32}$

(where 1.387 = $(1350/3600)^{-1/3}$ is due to the influence of temperature)

duration (s) of the fireball = 0.299 x 26.29 $M^{0.32}$

(where 26.29 = $(3600/1350)^{10/3}$ is due to the temperature)

and radius (m) for unbearable pain = 8.59 $M^{1/3}$

*t : duration of fireball

We have compared the results given by these formula in table 5.

Table 5

BLEVE Heat effects from LPG spheres

Volume m^3	500	1000	1500	500	1000	1500
Nature of LPG	butane	butane	butane	propane	propane	propane
Mass M of liquefied gas when 90 % filled (kg)	251500	503000	755000	226000	452000	678000
Radius of fire ball according to T.N.O. $R = 3.24\ M^{0.325}$ (m)	184	231	264	178	223	254
Radius for 1% lethality according to T.N.O. $R = 3.12\ M^{0.425}$ (m)	616	827	982	588	790	938
Radius for significant burns according to T.N.O. $R = 4.71\ M^{0.407}$ (m)	743	985	1162	711	943	1112
Duration of the fire ball according to TNO $t = 0.852\ M^{0.26}$ (s)	21,6	25,87	28,75	21,01	25,16	27,96
Radius of the fire ball according to UCSIP $2(M)^{1/3}$ (m)	126	159	182	122	153	175
Radius for lethality according to UCSIP $7.182\ M^{1/3}$ (m)	452	571	653	437	549	628
Radius for significant burns according to UCSIP $10.157\ M^{1/3}$ (m)	640	808	924	620	777	889
Duration of the fire ball according to Nazarian $t = 0.45\ M^{0.333}$ (s)	28,43	35,0	41	27,42	34,6	39
Diameter of the fire ball according by Strehlow $d = 3.86 \times 1.387\ M^{0.32}$ (m)	285	358	406	276	345	392
Duration of the fire ball according to Strehlow $t = 7.86\ M^{0.320}$ (s)	417	522	593	403	504	573
Radius for unbearable pain according to Strehlow $r = 8.59\ M^{0.333}$ (m)	541	683	782	524	657	751

When comparing these results, it is evident that there are large discrepancies (mainly related to the values of emissive powers, the position of the fireball, the attenuation by air). Very likely, these evaluations by STREHLOW on one hand and by others on the other hand cannot be compared. Nevertheless, the use of adimensional groupation is interesting.

Until now we propose the use of TNO formula (18).

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 contents of the vessel just before bursting open - the atmospheric boiling points of the liquid).

Assuming an overheating of 150 K, it is possible to calculate the radii for pressure thresholds of 170 mbar and 50 mbar.

radius (m) for lethality (at a few % probability pressure threshold = 170 mbar) = $3.84\ (M)^{1/3}$

radius (m) for reversible wounds (pressure threshold = 50 mbar) = $8.70\ (M)^{1/3}$

For example 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 50 mbar), calculated by the above formula is 792 m.

It can be concluded that 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 effect), one need to consider mainly the radiation effects. But it might be pointed out that, until now, the delay of occurrence 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 flammable dusts.

Figure 5

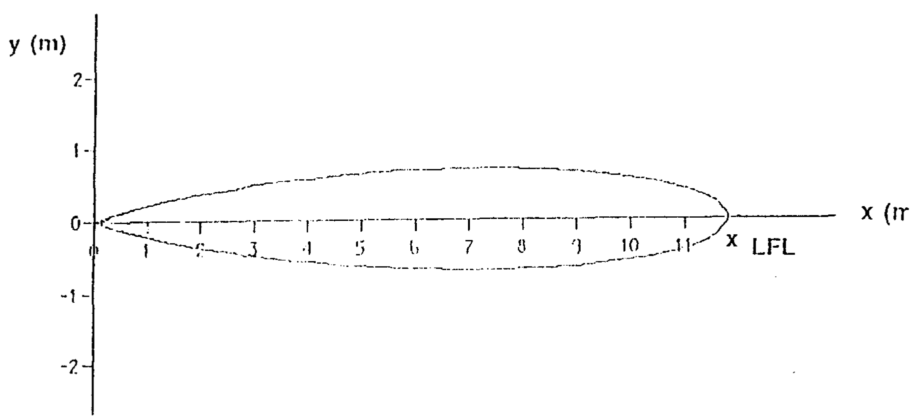


Table 6

Discharge from a 120 dm^3 vessel under 10 MPa pressure

GAS	HOLE DIAMETER (mm)	VESSEL PRESSURE (bar)	x_{LFL} (m)	
			CALCULATED	EXPERIMENTAL
H_2	6	36	12	9.5
	12	12	16	12.5
CH_4	12	33	6.4	6
	24	25	11.2	9

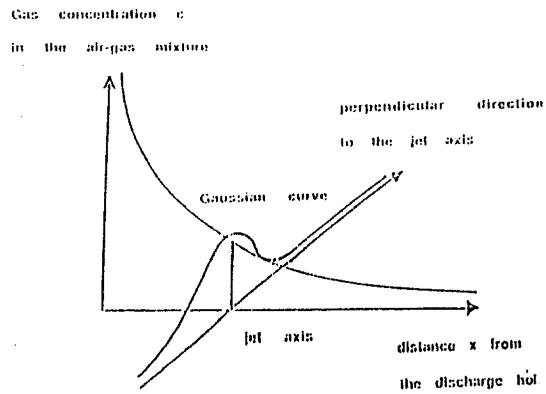
V.1. Unconfined explosions.

With gases and vapors, DAVENPORT (19) pointed out that only a small part of the released gas is generally involved in the explosion.

Such an explosion occurred 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 on H_2-CH_4 (H_2/CH_4 3) were released, after the breakage of a connecting duct as a guillotine opening. 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 H_2-CH_4 mixture (out of an amount of 160 kg released) was involved in the explosion. After close examination of the mechanical damages, the TNT equivalent could be assumed as 5 kg. In these particular conditions, only the turbulence was responsible of the mixing process before this explosion. The ignition source was unknown but the ignition occurred a few seconds after the release.

In the survey of the hazards for assuming the maximum effects of the explosion, the time lag at which the initiation of the explosion occurred is as important as the source location in order to define the safety distances. Unfortunately, a few codes can describe the generation of a cloud, particularly when it results from the discharge in air of a vessel pressurized by a flammable gas. We established a code describing the variation with time of the dimensions of the flammable cloud and validated it by testing the horizontal discharge in air of a 120 dm^3 vessel pressurized by 10 MPa of H_2 or CH_4 through a hole of diameter d($6<d<24$ mm). Finally it was concluded that the volume of the zone, where the air-gas mixture is flammable, is characterized by an increasing phase followed by a decreasing phase ; the profile of the concentration versus distance curve (fig. 4) is hyperbolic as in a stationary jet . Calculated (JET 1 code) and experimental values for the distance at which the lower flammability limit -xLFL- is obtained is given in table 6 (20). An example of the calculated xLFL contour can be seen on figure 5.

Figure 4



The JET 1 code is able to calculate the volume of the flammable mixture in the decreasing phase in the choosen operating conditions. At the moment, tests with higher values of the vessel volume and of the hole diameter would be necessary to have longer increasing phases and to predict the instant of the transition between the two phases when the flammable volume is at its maximum. Nevertheless this volume remains very low (5 to 10 % of the initial amount of flammable gas).

x x x

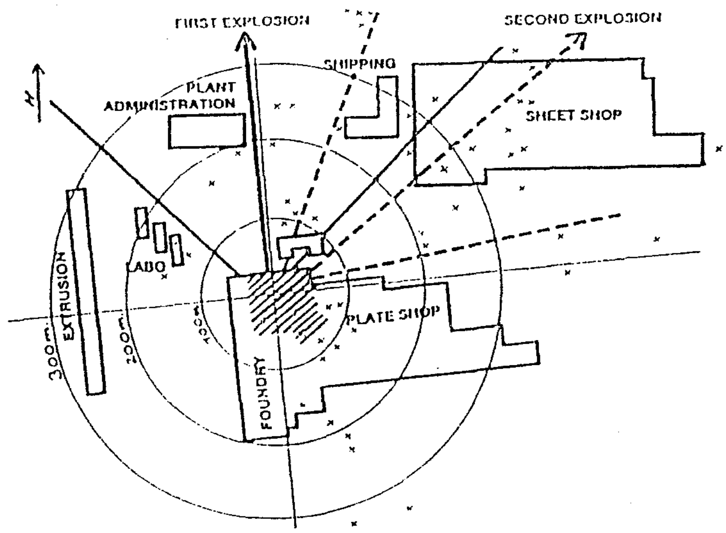
But explosions are also possible in confined spaces.

V.2. Confined explosions.

For example, in 1986 in a casting line, a very violent aluminum explosion occurred causing the death of 4 people, injuring 25 others and with extensive material damage. Lightning was recognized as the initial factor of the explosion. A modest amount of the lightning energy was involved in the vaporisation and atomisation process of liquid aluminum. The resulting vapors and droplets, mixed with air ignited by the lightning, 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 aluminum 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 as examplified on figure 6. This figure shows the asymetrical projection of debris with some screening effects given by the foundry equipment located westwards from the center of the explosion. This projection field is hardly calculable.

Figure 6

Aluminum explosion : projection field of 52 missiles (x)
(mean weight : 62 kg, maximum landing distance : 600 m)



Every year, a lot of accidental dust explosions occurred 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 buldings, concrete missiles must be thrown. In 1982 a barley and malt dust explosion occurred in Metz, France and induced the collapse of nine 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 20 000 t cells and 1 x 40 000 t cell).

The two 20 000 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 (40 000 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./ CONCLUSION.

The critical analysis of hazards studies and accident connected to pool fires, BLEVES 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 thresholds and the energy thresholds for missile effects are generally based on experience gained after accident investigation or intentional explosions.

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

For pressure thresholds, the effects on human beings are quite well understood ; but for facilities, only scattered data are available. Validations by experiments with existing physical models are needed with close examination of the effect of reflected pressures and of small TNT charges (less than 100 kg).

Heat radiation thresholds are to be choosen differently whether Bleves or large pool fires are involved.

As an energy threshold for missile effect, values between 20 joules (used in pyrotechnic plants) and 100 joules (related to observations after accidental explosions) are likely.

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

As regards pool fires, calculation means are consistent to evaluate the heat radiated from LPG 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 strongly influenced by the type of equipment and preventive means (insulation, external water, steam or foam spraying) and rather unpredictable.

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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