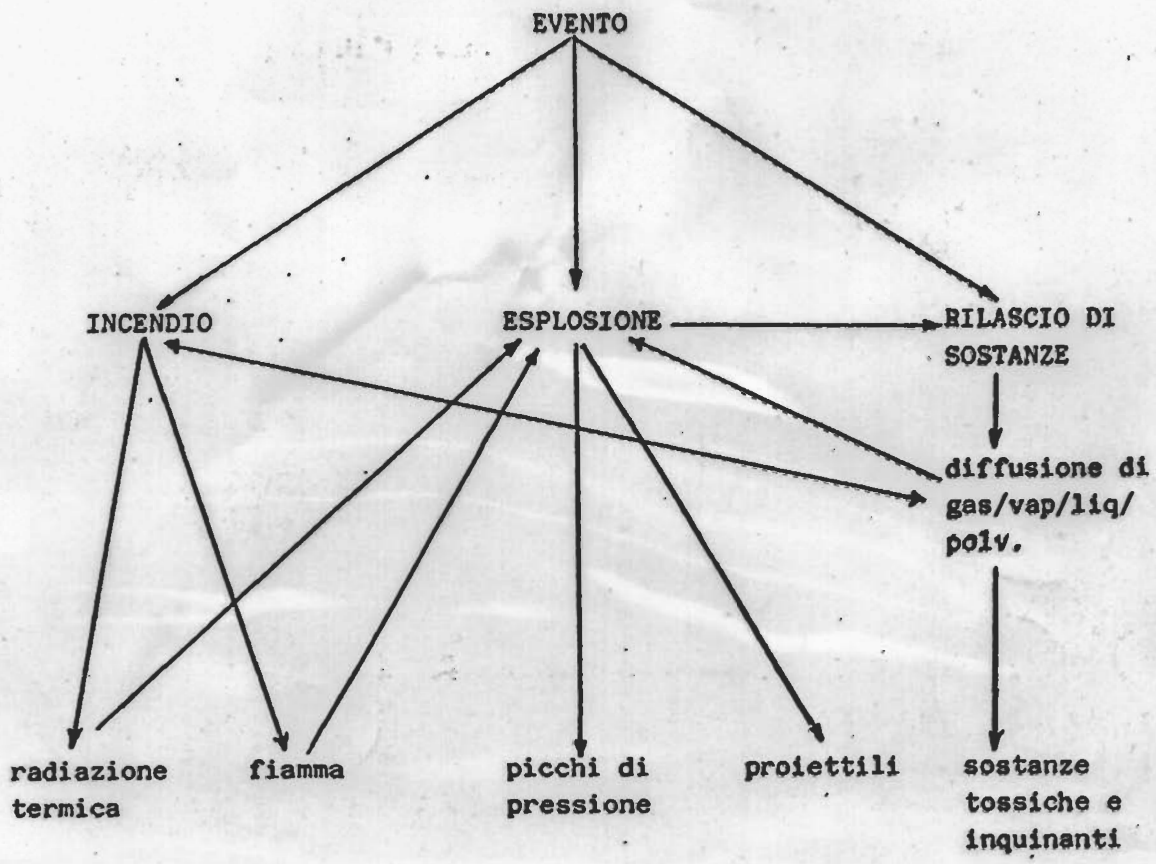


FIGURA 2 - Sviluppo dei fenomeni incendio, esplosione e rilascio di sostanze tossiche e inquinanti.

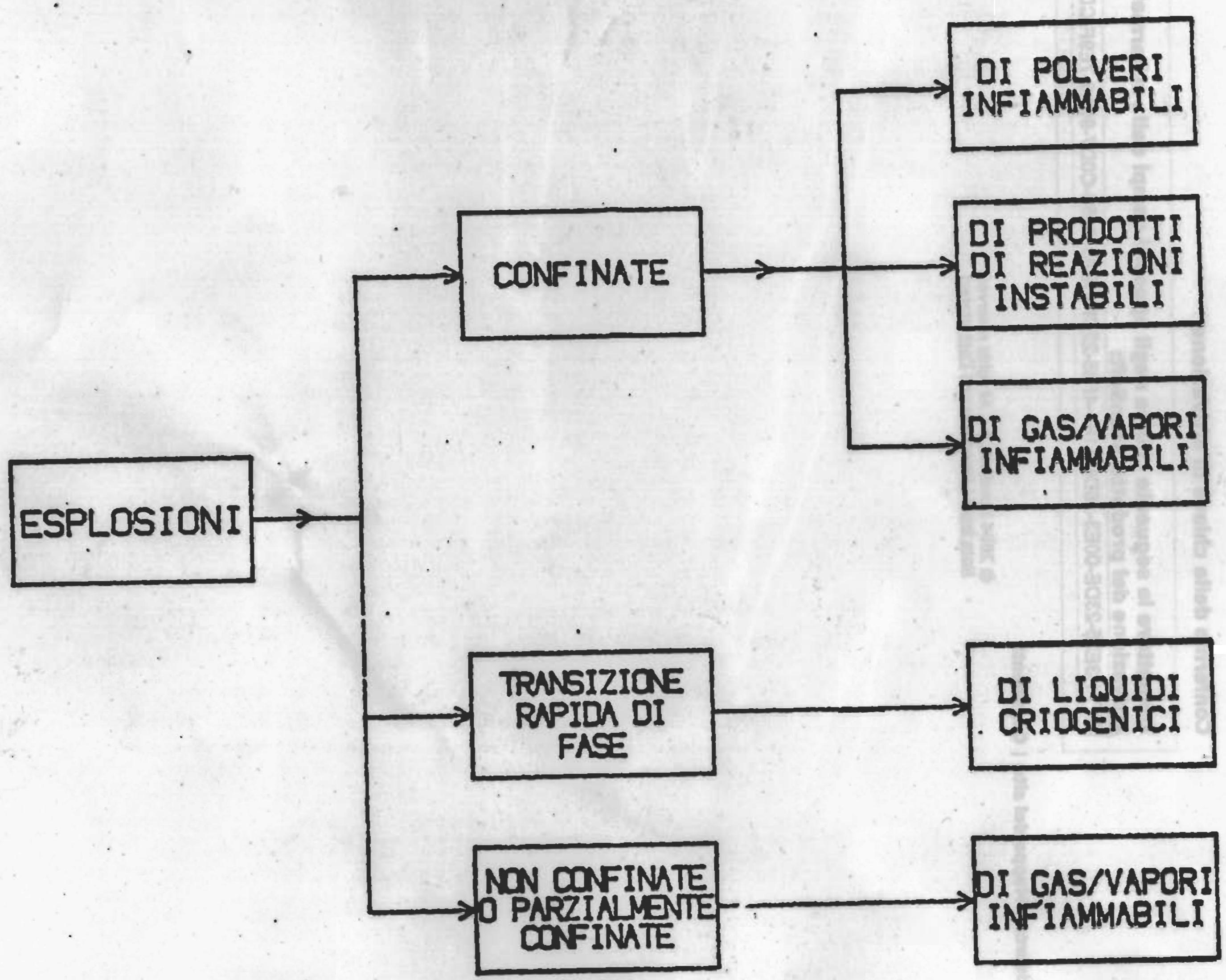
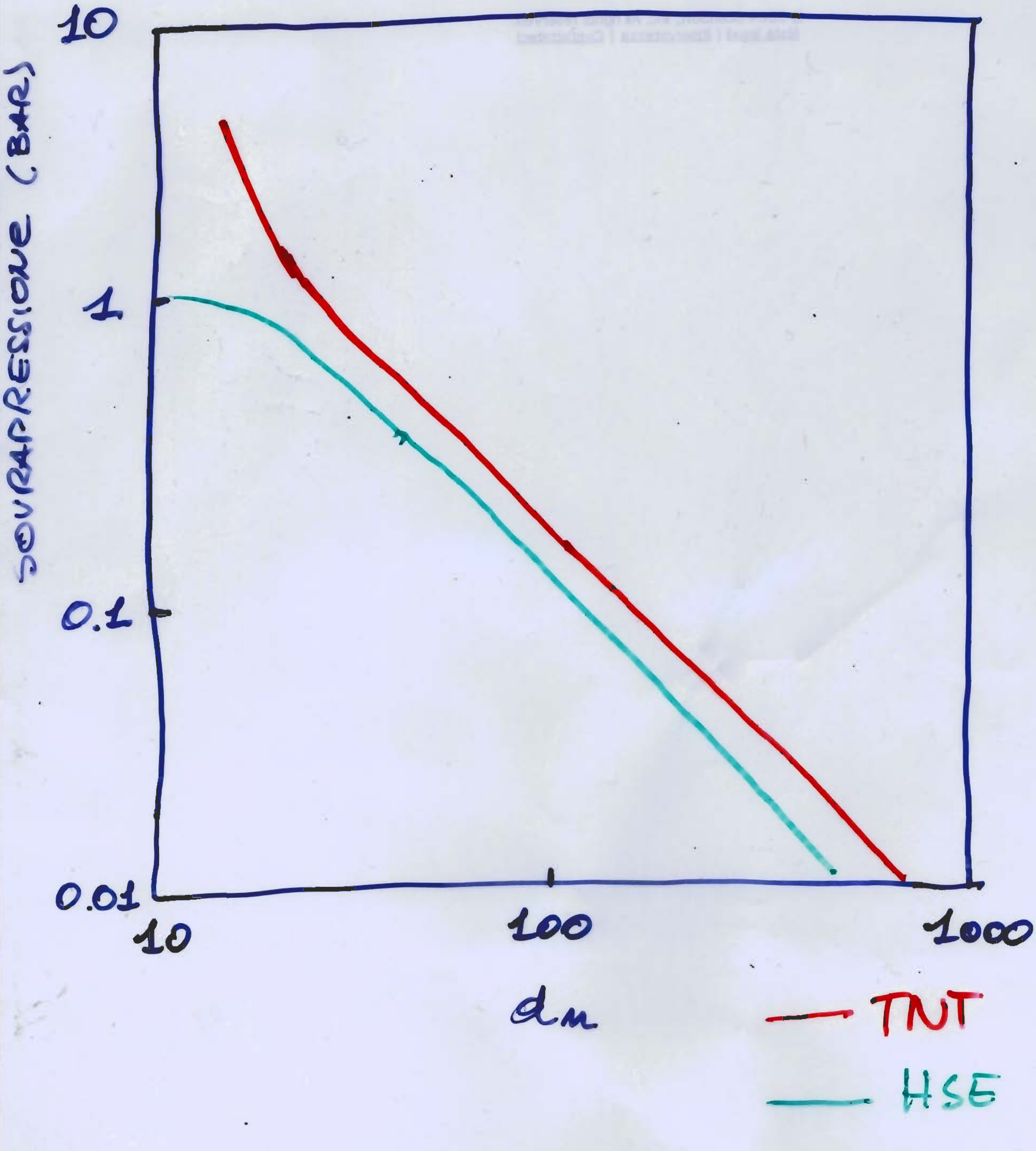


FIGURA 5 - Schema tipi di esplosioni <2>

MODELLO TNT

$$W_{TNT} = \eta \frac{H_C}{4{,}198 \cdot 10^6} W_v$$

$$d_n = \frac{d}{\sqrt[3]{W_{TNT}}}$$



maximum possible effect would be experienced. Traffic should be considered in this analysis as an ignition source (Section 5.2).

Models of UVCEs are primarily based on three broad approaches (Opschoor and Schecker, 1983):

- detonating high explosive equivalence (e.g., TNT model)
- correlations with observed UVCEs (e.g., TNO model)
- idealized gas dynamic models (e.g., Acoustic model)

The TNT model is easy to use and has been applied for many CPQRAs. It is described in Decker (1974), Stull (1977), Lees (1980), and Baker et al. (1983). It is based on the assumption of equivalence between the flammable material and TNT, factored by an explosion yield term:

$$W = \frac{\eta M E_c}{E_{c_{TNT}}} \qquad (2.2.1)$$

where W = equivalent mass of TNT (kg or lb)
M = mass of flammable material released
η = empirical explosion yield (or efficiency) (ranges from 0.01 to 0.10)
E_c = lower heat of combustion of flammable gas (kJ/kg or Btu/lb)
$E_{c_{TNT}}$ = heat of combustion of TNT (4437–4765 kJ/kg, or 1943–2049 Btu/lb).

The flammable cloud explosion yield is empirical, with most estimates varying between 1 and 10% (Brasie and Simpson, 1968; Gugan, 1979; Lees, 1980). Bodurtha (1980) gives the upper limit on the range of yields as 0.2. Eichler and Napademsky (1978) from review of historical data conclude the maximum expected yield is 0.2 for a symmetric cloud, but could be significantly higher—up to 0.4 for an asymmetric cloud. This factor is based on analysis of many UVCE incidents. As doubt exists as to the actual mass involved in many UVCE incidents, the true yield is uncertain. Prugh (1987) gives a helpful correlation of flammable mass versus UVCE probability from historical data. Decker (1974) shows how to link a Gaussian dispersion model with the TNT model.

The explosion effects of a TNT charge are well documented, as shown in Figure 2.18 for a hemispherical TNT surface charge. The pressure which would be recorded on the side of a structure parallel to the blast is the side-on overpressure or P_{SO}. The reflected pressure, P_r, is the pressure on a structure perpendicular to the shock wave and is at least a factor of 2 greater than the side-on overpressure. The impulse parameters are also important when explosion effects are considered (Section 2.3.3).

The various explosion parameters are plotted as a function of the scaled range, Z_G. The scaled range is defined as distance divided by the cube root of TNT mass (W). Overpressure in this diagram in excess of 15 psig (1 bar) should be ignored since the peak value observed in UVCEs is approximately 15 psig (Health and Safety Executive, 1979).

The TNO Correlation Model (Wiekema, 1979) was developed to avoid the necessity of developing a high explosive equivalent for the vapor cloud since the

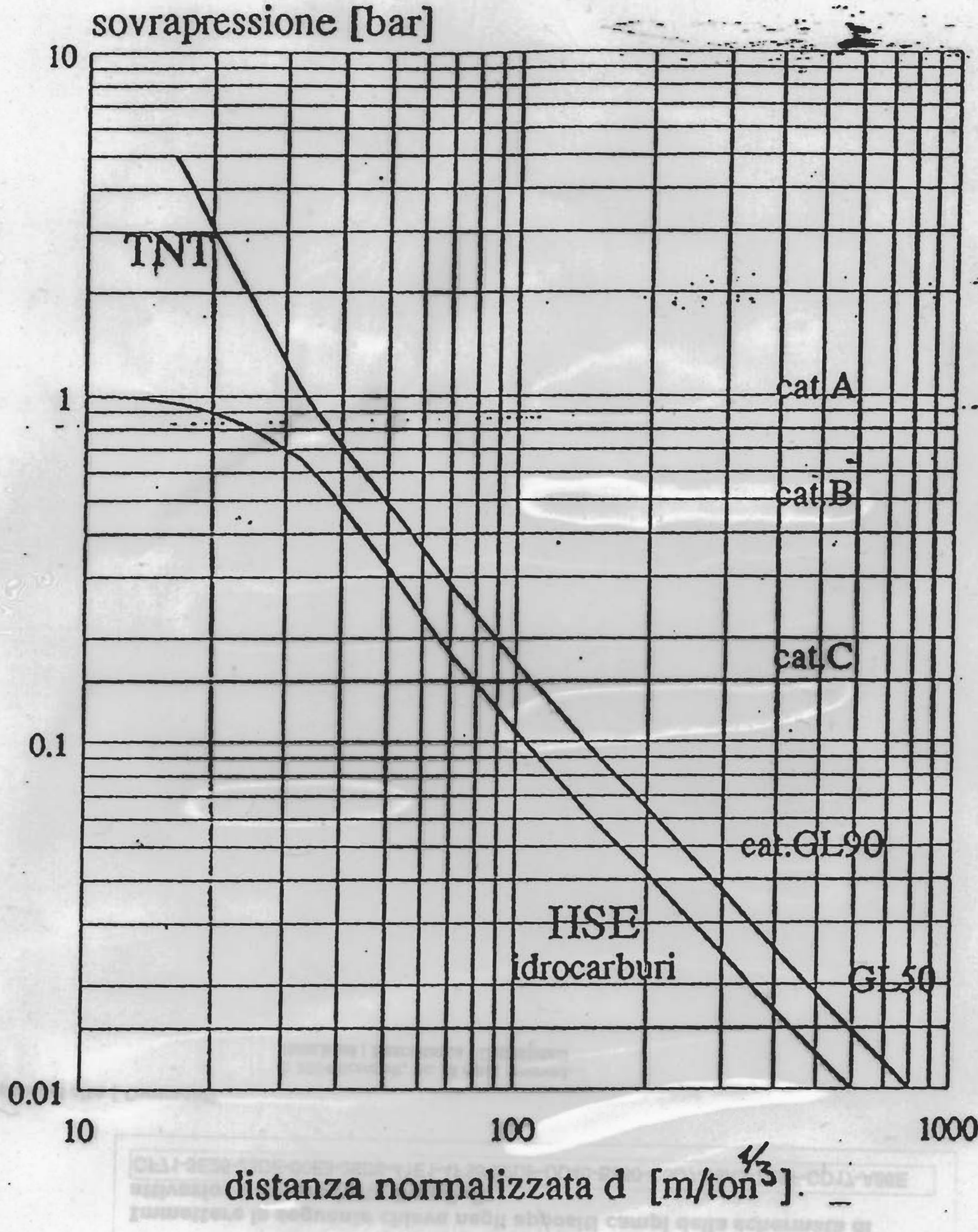
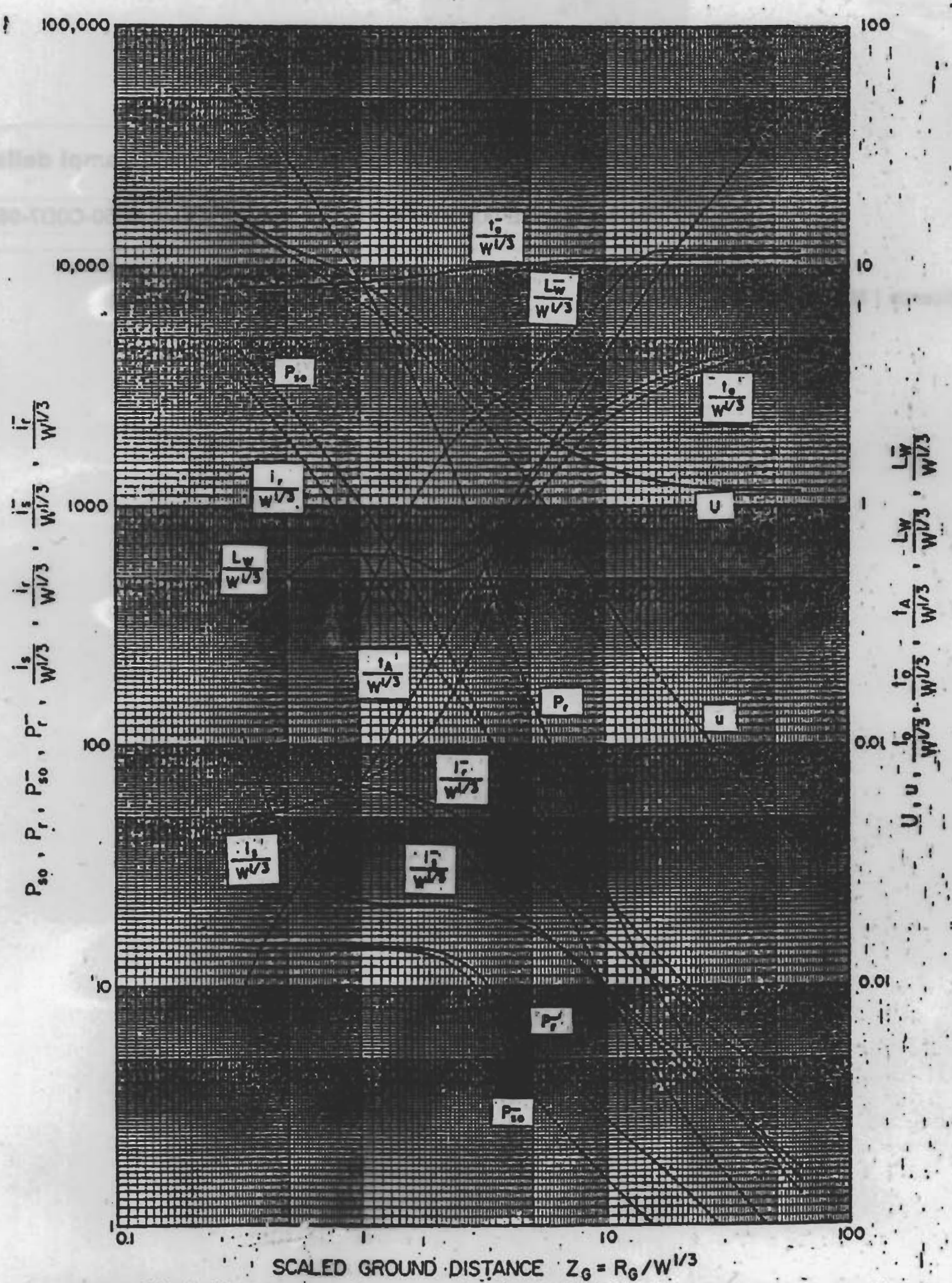
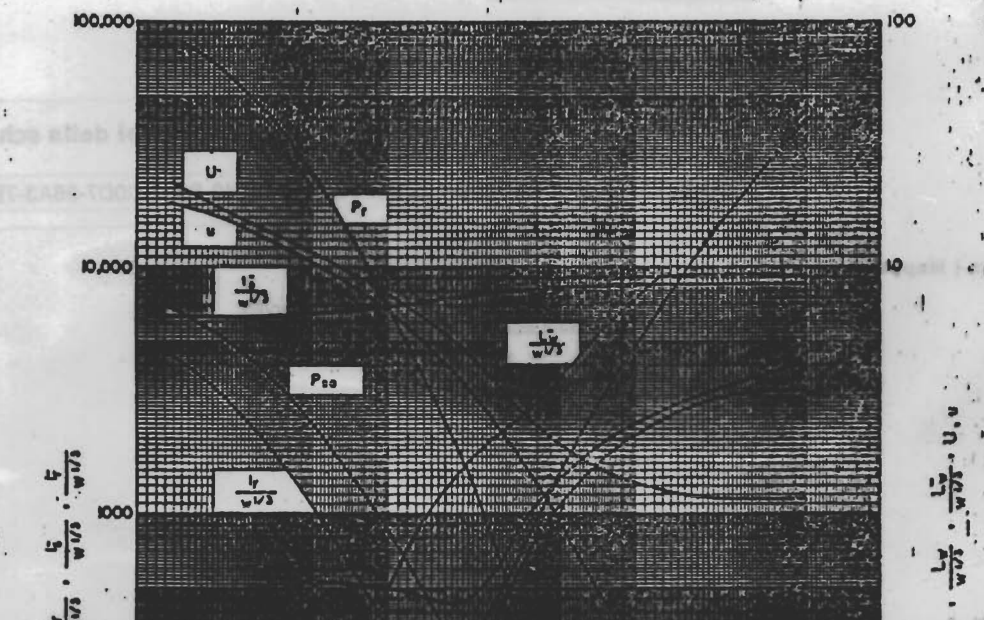


Figura 7.25. Metodo del TNT equivalente.



P_{so} = peak positive incident pressure, psi
P_{so}^- = peak negative incident pressure, psi
P_r = peak positive normal reflected pressure, psi
P_r^- = peak negative normal reflected pressure, psi
$i_s/W^{1/3}$ = scaled unit positive incident impulse, psi-ms/lb$^{1/3}$
$i_s^-/W^{1/3}$ = scaled unit negative incident impulse, psi-ms/lb$^{1/3}$
$i_r/W^{1/3}$ = scaled unit positive normal reflected impulse, psi-ms/lb$^{1/3}$
$i_r^-/W^{1/3}$ = scaled unit negative normal reflected impulse, psi-ms/lb$^{1/3}$
$t_A/W^{1/3}$ = scaled time of arrival of blast wave, ms/lb$^{1/3}$
$t_o/W^{1/3}$ = scaled positive duration of positive phase, ms/lb$^{1/3}$
$t_o^-/W^{1/3}$ = scaled negative duration of positive phase, ms/lb$^{1/3}$
$L_w/W^{1/3}$ = scaled wavelength of positive phase, ft/lb$^{1/3}$
$L_w^-/W^{1/3}$ = scaled wavelength of negative phase, ft/lb$^{1/3}$
U = shock front velocity, ft/ms
u = particle velocity, ft/ms
W = charge weight, lbs
R_G = radial distance from charge, ft
Z_G = scaled ground distance, ft/lb$^{1/3}$

Figure 2.18. Shock-wave parameters for hemispherical TNT surface explosion at sea level (US Army, 1969).



P_{so} = peak positive incident pressure, psi
P_{so}^- = peak negative incident pressure, psi
P_r = peak positive normal reflected pressure, psi
P_r^- = peak negative normal reflected pressure, psi
$i_s/W^{1/3}$ = scaled unit positive incident impulse, psi-ms/lb$^{1/3}$
$i_s^-/W^{1/3}$ = scaled unit negative incident impulse, psi-ms/lb$^{1/3}$
$i_r/W^{1/3}$ = scaled unit positive normal reflected impulse, psi-ms/lb$^{1/3}$
$i_r^-/W^{1/3}$ = scaled unit negative normal reflected impulse, psi-ms/lb$^{1/3}$
$t_A/W^{1/3}$ = scaled time of arrival of blast wave, ms/lb$^{1/3}$
$t_o/W^{1/3}$ = scaled positive duration of positive phase, ms/lb$^{1/3}$
$t_o^-/W^{1/3}$ = scaled negative duration of positive phase, ms/lb$^{1/3}$
$L_w/W^{1/3}$ = scaled wavelength of positive phase, ft/lb$^{1/3}$
$L_w^-/W^{1/3}$ = scaled wavelength of negative phase, ft/lb$^{1/3}$
U = shock front velocity, ft/ms
u = particle velocity, ft/ms
W = charge weight, lb
R = radial distance from charge, ft
Z = scaled distance, ft/lb$^{1/3}$

Figure 2.20. Shock-wave parameter for spherical TNT explosion in free air at sea level (US Army, 1969).

2.2.2.2 DESCRIPTION

Description of Technique. Baker et al. (1983) describe a technique for estimating overpressure for a rupture of a gas filled container based on small scale experimental studies. Other methods relate directly to calculation of a TNT equivalent energy and use of shock wave correlations as in Figure 2.18. There are various expressions that can be developed for calculating the energy released when a gas initially having a volume, V, expands in response to a decrease in pressure from a pressure, p_1 to atmospheric pressure, p_0 (Brown, 1985). If it is assumed that expansion occurs isothermally and that ideal gas laws apply the following equation can be derived.

$$W = 1.4 \times 10^{-6}\, V[P_1/P_0][T_0/T_1]RT_1 \ln[P_1/P_2] \qquad (2.2.3)$$

where
W = energy in lb TNT
V = volume of compressed gas, ft^3
P_1 = initial pressure of compressed gas, psia
P_2 = final pressure of expanded gas, psia
P_0 = standard pressure, 14.7 psia
T_1 = temperature of compressed gas, °R
T_0 = standard temperature, 492°R
R = gas constant, $\dfrac{1.987\ \text{Btu}}{\text{lb mol-°R}}$
1.4×10^{-6} = conversion factor (this factor assumes that 2000 Btu = 1 lb TNT)

The calculated equivalent amount of TNT energy can now be used to estimate shock wave effects. As in unconfined vapor cloud explosions, the analogy of the explosion of a container of pressurized gas to a condensed phase point source exploiton of TNT is not appropriate in the near field. Prugh (1988) suggests a correction method using a virtual distance from an explosion center based on work by Baker et al. (1983) and Petes (1971).

The blast pressure, P_s, at the surface of an exploding pressure vessel can be estimated from the following expression (Prugh, 1988):

$$P_b = P_s\{1 - [3.5(\gamma - 1)(P_s - 1)]/[(\gamma T/M)(1 + 5.9P_s)]^{0.5}\}^{-2\gamma/(\gamma-1)} \qquad (2.2.4)$$

where P_s = pressure at surface of vessel, bara
P_b = burst pressure of vessel, bara
γ = ratio of specific heats, C_p/C_v
T = absolute temperature, °K
M = molecular weight of gas, lb/lb mole

The above equation assumes that expansion will occur into air at atmospheric pressure at a temperature of 25°C. A trial and error solution is required because the equation is not explicit for P_s.

Knowing the blast pressure at the surface, P_s, the scaled distance, Z, for the explosion can be obtained from Figure 2.18. Many pressure vessels are near

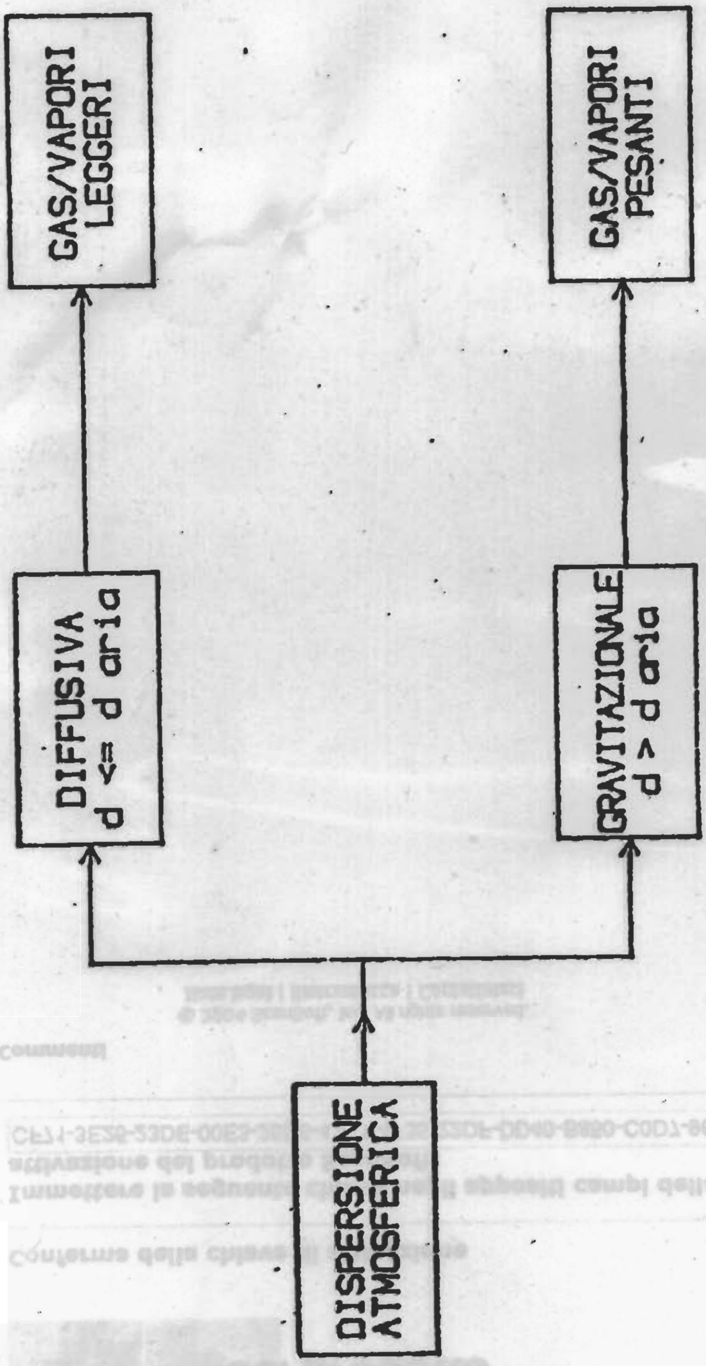


FIGURA 6 - Schema tipi di dispersione atmosferica <3>

La frazione di liquido che vaporizza in conseguenza del rilascio (da aggiungere alla quantità di vapore inizialmente presente nel recipiente) è valutabile con la relazione:

$$x = 1 - e^{-C_\ell (T_i - T_b)/r}$$

ove:	C_ℓ	=	**calore specifico della sostanza**	**(J/Kg. K)**
	T_i	=	**temperatura media del liquido al momento della rottura**	**(K)**
	T_b	=	**punto di ebollizione della sostanza**	**(K)**
	r	=	**calore latente di vaporizzazione della sostanza**	**(J/Kg)**

$$\frac{\Delta p}{p_0} = 0.2177\left(\frac{r}{L_0}\right)^{-1} + 0.1841\left(\frac{r}{L_0}\right)^{-2} + 0.1194\left(\frac{r}{L_0}\right)^{-2} \quad \text{per } \frac{r}{L_0} > 1.088 \qquad (7.66'.)$$

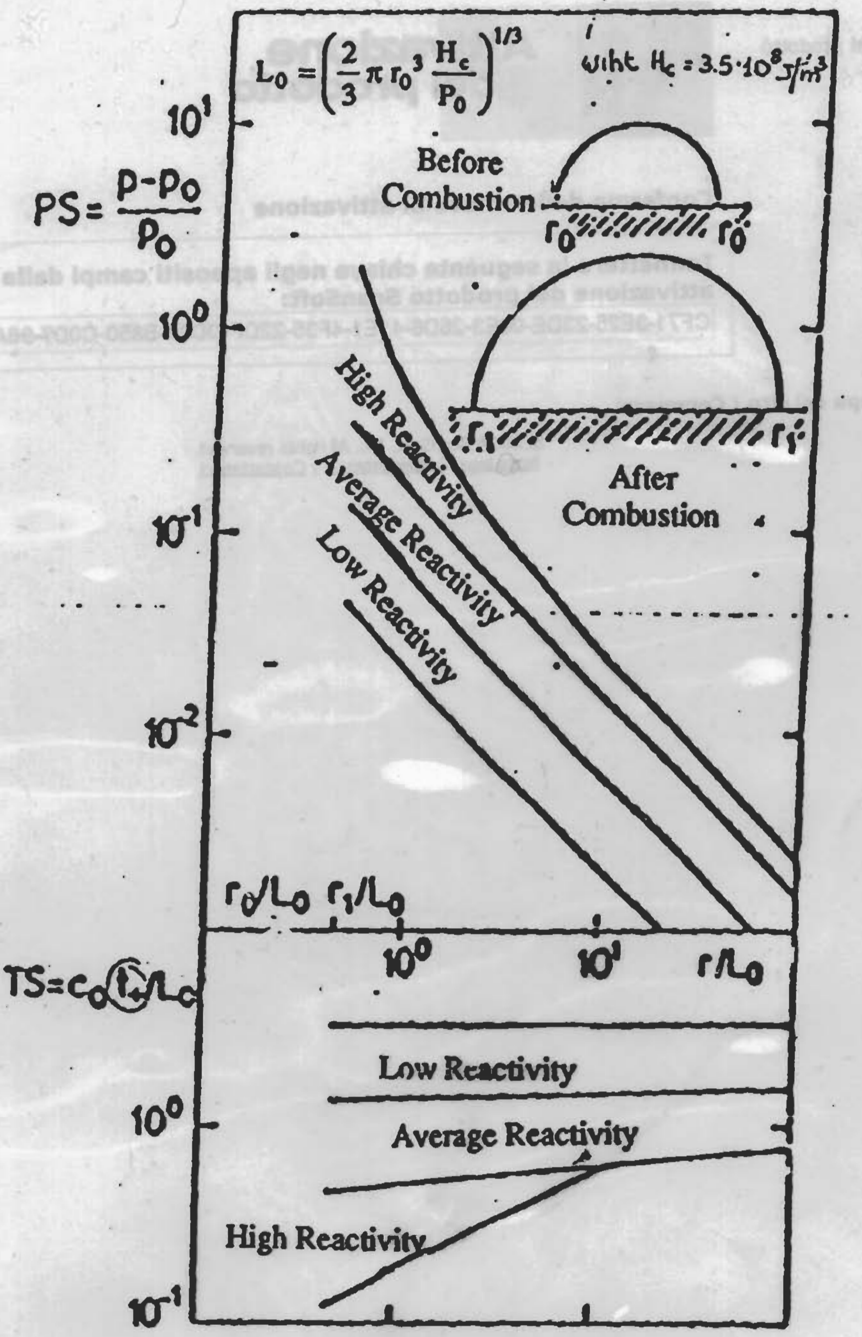


Figura 7.27. Illustrazione del modello TNO.

MODELLO TNO

- $$\Delta P = K\, P_0 \left[\frac{L_0}{r}\right]$$

$$L_0 = \sqrt[3]{\frac{V_{ott}}{P_0}} = \sqrt[3]{\frac{E_c H_c}{P_0}}$$

DOVE

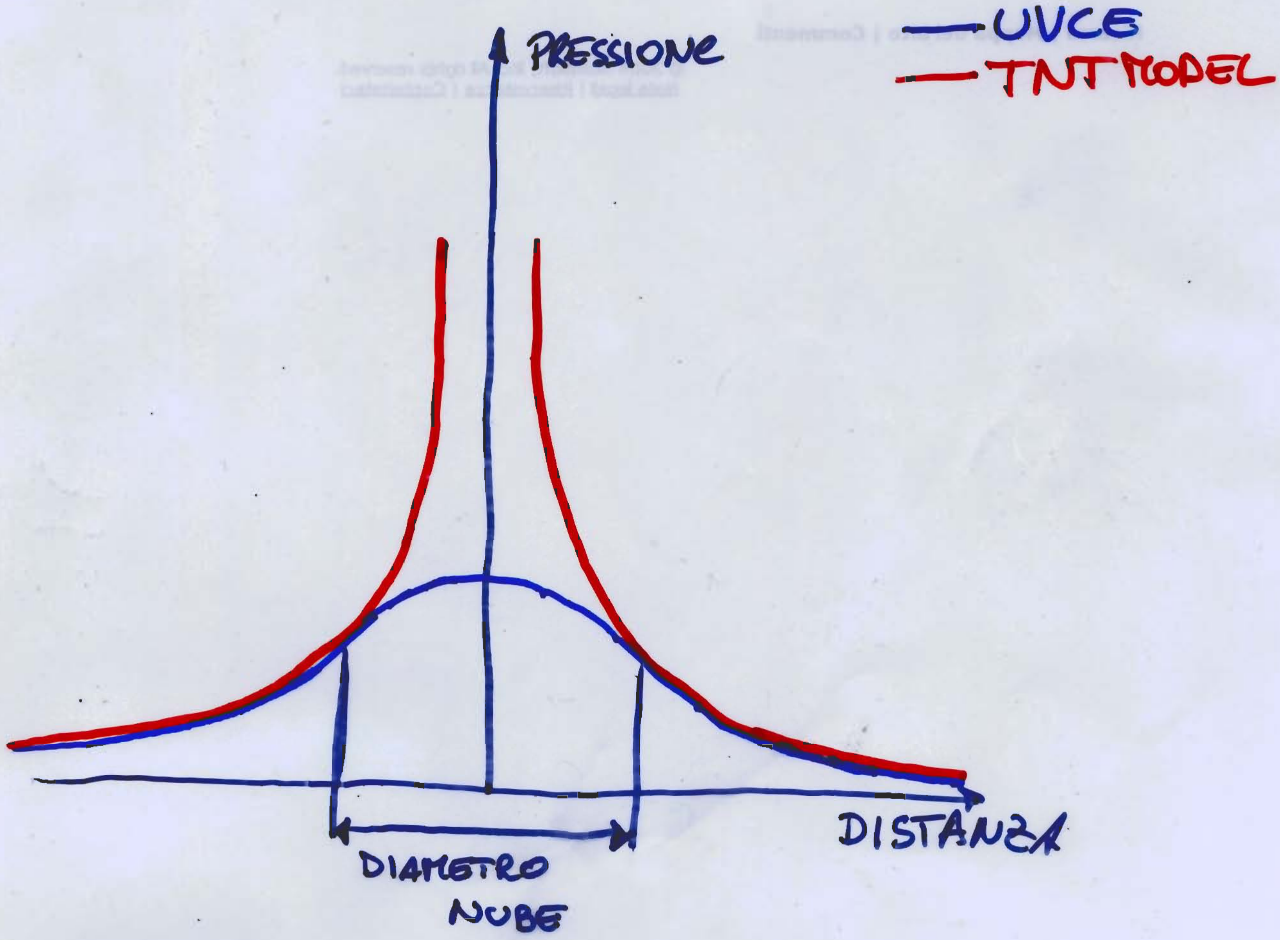
$S_f = 40\ m/s$ $\quad k = 0.02$

$S_f = 80\ m/s$ $\quad k = 0.06$

$S_f = 160\ m/s$ $\quad k = 0.15$

- $$\begin{cases} \dfrac{\Delta P}{P_0} = 0.2177\left[\dfrac{r}{L_0}\right]^{-1} + 0.1841\left[\dfrac{r}{L_0}\right]^{-2} + 0.1194\left[\dfrac{r}{L_0}\right]^{2} & \text{per } \dfrac{r}{L_0} > 1.088 \\ \dfrac{\Delta P}{P_0} = 0.518\left[\dfrac{r}{L_0}\right]^{-1.7} & \text{per } 0.29 < \dfrac{r}{L_0} < 1.088 \end{cases}$$

SCOSTAMENTO DALL'IDEALITÀ PER UVCE



3. ESPLOSIONI

3.1. ESPLOSIONI NON CONFINATE (UVCE)

A seguito del rilascio all'esterno di una massa notevole di vapori infiammabili puo' formarsi una nube in condizioni di esplosivita'. Se innescata la nube da luogo ad un fenomeno deflagratorio, con possibile transizione, in particolari condizioni di parziale confinamento, a fenomeni detonatori. Il calcolo delle distanze caratteristiche dei danni conseguenti la deflagrazione procede come descritto nel seguito. Detta m (kg) la massa totale di combustibile nel campo di infiammabilita' presente nella nube ed h_c (J/kg) il calore di combustione, l'energia totale disponibile E (J) si ricava da :

$$E = m \cdot h_c \qquad (64)$$

Se $E < 5*10^7$ J si possono assumere come praticamente trascurabili gli effetti dell'esplosione. Solo una parte dell'energia totale E viene convertita in onde di pressione :

$$E_p = e_c \, e_m \, E \qquad (65)$$

dove E_p = energia convertita in onde di pressione (J)

e_c = coefficiente di correzione delle disuniformita' stechiometrica nella nube

e_m = rendimento meccanico della esplosione

Secondo Wiekema-34 e' ragionevole assumere, per la maggior parte degli idrocarburi, $e_c = 0.3$ ed $e_m = 0.33$, da cui risulta $E_p \approx 0.1$ E .

Le distanze massime caratteristiche di danno sono calcolabili con le seguenti relazioni derivate sperimentalmente da Brasie-Simpson-35 :

$$R(S) = C(S)\ E_p^{1/3} \qquad (66)$$

dove R(S) = distanza massima a cui si hanno danni di categoria S (m)

C(S) = costante caratteristica di danno ($mJ^{-1/3}$)

I valori di C (S) suggeriti sono :

C(S)	categoria di danno
0.03	danni gravi agli edifici ed ai macchinari
0.06	danni riparabili agli edifici
0.15	rottura totale dei vetri con feriti da scheggie
0.40	rottura del 10% dei vetri.

Per un calcolo piu' dettagliato delle sovrapressioni e delle durate dell'impulso alle varie distanze dall'epicentro dell'esplosione, si puo' utilizzare il metodo del "pistone equivalente" sviluppato da Pasman ed al. - 36.

Detto V_o il volume iniziale della nube e V_1 il volume finale dopo l'esplosione, il movimento di espansione e' rappresentabile come un pistone che genera un'onda d'urto, spostandosi tanto piu' rapidamente quanto piu' reattivo e' il gas che da origine al fenomeno.

I gas possono essere suddivisi in tre categorie (poco reattivi, mediamente reattivi, molto reattivi) contraddistinte dai seguenti valori di velocita' di spost. del fronte di fiamma :

cat. 1 $u_{FL} = 40 \ ms^{-1}$ (es. metano)

cat. 2 $u_{FL} = 80 \ ms^{-1}$ (es. propano)

cat. 3 $u_{FL} = 160 \ ms^{-1}$ (es. acetilene)

Si procede quindi a calcolare la lunghezza caratteristica dell'esplosione L_o, dalla relazione :

$$L_o = (V_o E_c / p_o)^{1/3} \qquad (67)$$

dove V_o = volume totale della miscela stechiometrica aria - combustibile (m^3)

E_c = potere calorifico della miscela ($J \ m^{-3}$)

p_o = pressione prima della deflagrazione

L'incremento di pressione alla distanza r dall'epicentro della deflagrazione e' calcolabile con le relazioni :

$$\delta p/p_o = 2 * 10^{-2} * L_o/r \quad \text{per gas di cat. 1} \qquad (68)$$

$$\delta p/p_o = 6 * 10^{-2} * L_o/r \quad \text{per gas di cat. 2} \qquad (69)$$

$$\delta p/p_o = 15 * 10^{-2} * L_o/r \quad \text{per gas di cat. 3} \qquad (70)$$

Nel caso si abbia una detonazione, le equazioni precedenti sono state modificate da Brinkley-Kirkwood - 37 a seguito degli studi condotti da Kogarko - 38 :

$$\delta p/p_o = 0.518 \ (r/L_o)^{-1.7} \quad \text{per} \quad 0.29 \le r/L_o \le 1.088 \qquad (71)$$

$$\delta p/p_o = 0.2177*(r/L_o)^{-1}+0.1841*(r/L_o)^{-2}+0.1194*(r/L_o)^{-3} \quad (72)$$

$$\text{per } r/L_o > 1.088$$

In generale va comunque tenuto presente che la modellistica delle esplosioni non confinate di nubi di vapori infiammabili e' tuttora assai lacunosa e necessita di ulteriori studi (sugli effetti della forma della nube, sulla posizione ed il tipo di innesco, sui meccanismi di transizione da deflagrazione a detonazione ecc.); pertanto i risultati derivabili dalle eq. 64 - 72 vanno considerati con la necessaria prudenza. Per un approfondimento del problema si raccomanda la consultazione di Baker et al. - 39 e Gugan-40.

Nella fig. 17 e' riportato il diagramma delle sovrapressioni prodotte dalla deflagrazione di una massa di vapori di propano variabile da 1 a 1000 ton. Nella fig. 18 sono riportate le distanze caratteristiche di danno in funzione della energia di pressione disponibile nella nube.

Diagrammi del tipo di quelli di fig. 17 - 18 sono essenziali per calcolare i rischi per la popolazione e per dimensionare le sale controllo e le apparecchiature vitali di impianto in modo che sopravvivano alla esplosione iniziale.

allowance, use of next available plate thicknesses), vessel ultimate strengths can greatly exceed those assumed. TNO (1979) uses a lower value of 2.5 times MAWP, as European vessels can have a lower factor of safety. It is possible to be more precise if plate thickness, vessel diameter, and material of construction are known. A burst pressure can be estimated using the ultimate strength of the material and 100% weld efficiency in a hoop stress calculation. Specialist help is desirable for those calculations. Treatments of the bursting and fragmentation of vessels is given by Baker et al. (1978, 1983) and Brown (1985, 1986).

The explosion of a flammable mixture in a process vessel or pipework may be a deflagration or a detonation. Detonation is the more violent form of combustion, in which the flame front is linked to a shock wave. Well known examples of detonating gases are hydrogen, acetylene, and ethylene. A deflagration is a lower speed combustion process, but it may undergo a transition to detonation. This transition occurs in pipelines but is unlikely in vessels.

A dust explosion is usually a deflagration. Certain of the more destructive explosions in coal mines and grain elevators give strong indications that detonation was approached but efforts to duplicate those results have not been verified experimentally. Certain factors in the combustion of combustible dust are unique and as a result they are modeled separately from gases.

Venting cannot accommodate detonations.

- *Deflagrations*. For flammable gas mixtures, Lees (1980) summarizes the work of Zabetakis (1965) of the U.S. Bureau of Mines for the maximum pressure rise:

$$P_{2(max)}/P_1 = N_2T_2/N_1T_1 = M_1T_2/M_2T_1 \quad (2.2.18)$$

where M = molecular weight of the gas mixture
N = number of moles in the gas phase
T = absolute temperature of the gas phase
P = absolute pressure
max = peak value
1 = initial state
2 = final state

NFPA 68 (NFPA, 1988) also gives a cubic law relating rate of pressure rise to vessel volume in the form

$$(dP/dt)_{max}(V^{1/3}) = \text{characterization factor } (K_g \text{ for gases or } K_{St} \text{ for dusts})$$

Then it uses this relation, with experimentally derived values of K (which is a function of the composition, phase, ignition energy, and volume) to produce nomographs for calculating vent area to relieve a given overpressure. The guide also lists tables of experimental data for gases, liquids, and dusts that show P_{max} and dP/dt. Specific experimental data should be used whenever possible.

From these experimental data and from the relations given by

Zabetakis, maximum pressure rise for most deflagrations are typically

$$P_2/P_1 = 8 \text{ for hydrocarbon–air mixtures}$$

$$P_2/P_1 = 16 \text{ for hydrocarbon–oxygen mixtures}$$

where P_2 and P_1 are absolute pressures.

- *Detonation*. Lewis and von Elbe (1987) describe the theory of detonation, which can be used to predict the peak pressure and the shock wave properties (e.g., velocity and impulse pressure). Lees (1980) says the peak pressure for a detonation in a containment initially at atmospheric pressure may be about 20 bar (a 20-fold increase). This pressure can be many times larger if there is reflection against solid surfaces.
- *Dust Explosions*. NFPA 68 (1988), Bartknecht (1981), and Lees (1980) contain a considerable amount of dust explosion test data. The nomographs in NFPA 68 can be used to estimate the pressure within a vessel, provided the related functions of vent size, class of dust (St-1, 2, or 3), or K_{St}, vessel size, and vent release pressure are known. Nomographs for three dust classes

$$\text{St-1 for } K_{St} < 200 \text{ bar m/s}$$

$$\text{St-2 for } 200 < K_{ST} < 300 \text{ bar m/s}$$

$$\text{St-3 for } K_{St} > 300 \text{ bar m/s}$$

plus K_{St} values of 50–600 bar m/s are provided. Empirical equations are also provided that allow the problem to be solved algebraically.

In the case of low strength containers, similar estimates can be made using the equations outlined by Swift and Epstein (1987).

If the values of peak pressure calculated exceed the burst pressure of the vessel, then the consequences of the resulting explosion should be determined. As in Sections 2.2.2 and 2.2.3, the resulting effects are a shock wave, fragments, and a burning cloud. Although the pressure at which the vessel may burst may be well below the maximum pressure that could have developed, it is frequently conservatively assumed that the stored energy released as a shock wave is based on the maximum pressure which could have developed.

In chemical decompositions and detonations it is also frequently assumed that the available chemical stored energy is converted to a TNT equivalent.

The phenomenon of pressure piling is an important potential hazard in systems with interconnected spaces. The pressure developed by an explosion in Space A can cause pressure/temperature rise in connected space B. This enhanced pressure is now the starting point for further increase in explosion pressure. This phenomenon has also been seen frequently in electrical equipment installed in areas using flammable materials.

A small primary dust explosion may have major consequences if