Blast Wave Characteristics and Equivalency

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EXPLOSION DYNAMICS AND HAZARDS

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BLAST WAVE CHARACTERISTICS AND EQUIVALENCY

I. Sochet and H. Schneider

The characteristics of blast waves generated by detonation of gas clouds are studied theoretically and validated by both small-scale and large-scale experiments with ethylene–air mixtures of different equivalence ratio. The mixtures were confined in hemispherical or spherical balloons made from thin polyethylene foils of 0.75 m^3 and 15 m^3 in volume. The detonation of gas mixtures was initiated by a solid explosive. The characteristics of the blast wave in terms of overpressure, impulse, and duration of the positive phase obtained in this study were compared with those obtained in authors' previous work and with the principal results available in the literature. This comparison made it possible to raise the significant problem of the definition of equivalent TNT according to the scale at which the tests are carried out and according to the characteristic parameters of the blast wave. The sensitivity of equivalent TNT with respect to the reduced distance was clearly shown.

1 INTRODUCTION

This paper is focused on the effects of unconfined gas cloud explosions on the surrounding open environment in the context of safety for the protection of industrial or other types of installations. In order to protect both structures and personnel, it is necessary to estimate the pressure loads likely to result from any strong blast occurring in close proximity or further apart. This paper therefore focuses on detonations of explosive gas clouds.

Whether the detonation is accidental in origin or the result of a terroristic action, the effects produced require detailed investigation to assess the blast loads on structures. The effects on structures are analyzed in terms of overpressure, impulse, and duration.

When a hazard study is carried out in an industrial environment, it is still common practice to define the TNT equivalency as a single value to enable one to anticipate the mechanical consequences of an explosion. This is in spite of the results obtained by Dorofeev *et al.* [1], Formby and Wharton [2], and more

recently Dewey [3] demonstrating an evolution of the TNT equivalent according to the blast wave parameter (overpressure, impulse) and nondimensional distance. The present authors can confirm those results on the basis of small-scale tests conducted at the Laboratoire Energétique Explosions Structures (LEES, Bourges, France) and large-scale tests carried out at the Fraunhofer ICT (Karlsruhe, Germany).

The work presented here compares the blast waves resulting from the detonation of different explosive clouds with the blast wave produced by an equivalent charge of TNT. In order to conduct the study on the TNT equivalent, a number of experimental results [3–7], obtained with unconfined gaseous explosive clouds ranging from laboratory to full-scale tests, are considered. The results are compared with full-scale tests carried out at Fraunhofer ICT that have yet to be published [8]. These experiments involved ethylene–air mixtures in different proportions initially confined in balloons with volumes between 0.75 and 15 m^3. The balloons were placed at the ground level. The evolution of the TNT equivalent in terms of overpressure and impulse was determined from these experiments as well as from the results obtained in small-scale tests announced in the previous paper [7]. These TNT equivalents were also compared with the various other studies. All the results are presented in the nondimensional form.

2 EXPERIMENTS

2.1 Full-Scale Experiments of Fraunhofer Institute

The gas mixtures studied were ethylene–air mixtures with the following volume concentrations of fuel: 5.5%, 6.53%, and 10%, thereby covering several levels of equivalence ratio (fuel-lean, stoichiometric, and fuel-rich). Table 1 summarizes the compositions and chemical energy per unit of mass of the mixtures. The unconfined gas clouds were simulated using gas-filled balloons made from thin polyethylene envelopes 0.75 m^3 and 15 m^3 in volume. The balloons were either

Table 1 Composition and chemical energy of tested ethylene–air mixtures

$C_2H_4 + Z(0.21O_2 + 0.79N_2)$			
%(vol.) C_2H_4	Air moles number Z	Equivalence ratio ϕ	Chemical energy, MJ/kg
5.5	17.18	0.83	2.527
6.53	14.28	1.00	3.008
10	9.00	1.59	2.703

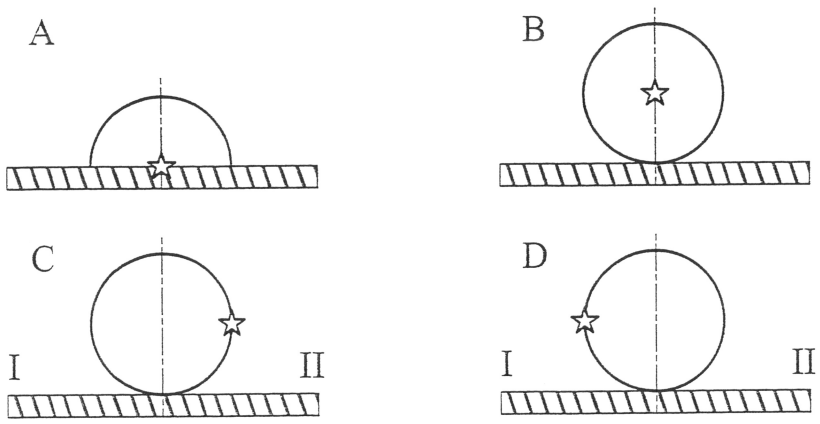

Figure 1 Configurations of experiments

hemispherical or spherical in shape. The volume of the hemispherical balloons ranged from 0.72 to 7.54 m^3 (with the radius from 0.70 to 1.53 m), corresponding to mixture mass between 0.93 and 15 kg. The volumes of spherical charges were varied from 1.45 to 14.33 m^3 (with the radius from 0.70 to 1.90 m), that is, with mixture mass between 1.82 to 17.3 kg. The spherical balloons were lying on the ground and consequently, the height of burst (HOB) was between 0.71 and 1.51 m. The different experimental configurations are shown in Fig. 1.

A solid explosive (50 g tetryl) was used as a primer for initiating a detonation of the gas mixtures. It was placed either at the center of the explosive cloud or at the balloon periphery. The evolution of the pressure in the blast wave produced by the detonation was recorded by ground-based sensors located at distances between 5 and 50 m from the explosion center, projected at a ground level along two radial directions on either side of the charge. The pressures measured were static pressures of the incident wave (configuration A). At the time the tests were carried out, the average atmospheric pressure was $9.93 \cdot 10^4$ Pa.

2.2 Small-Scale Experiments at LEES

As presented in earlier papers [7, 9], the laboratory-scale experiments were made with hemispherical (soap bubble) explosive charges in the case of ground-level explosions. The initial radius of the gaseous explosive charge ranged from 0.03 to 0.07 m. The gas premixture used was composed of propane and oxygen in stoichiometric proportions. A nominal electric energy of 200 J was discharged from a battery of capacitors during about 1 μs. Eight piezoelectric sensors mechanically insulated with rubber were positioned in the table plane at different radial distances from the center of the hemispheric volume (0.07, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7 m). The radial distances were all measured from the center of the explosive charge. The experiments were carried out at normal ambient temperature and pressure conditions as well as in a calm atmosphere.

3 SHOCK WAVE CHARACTERISTICS

The aim here is to present the experimental results and compare them with previous studies by different authors according to Sach's nondimensional quantities [6]. All the results were expressed in terms of variables:

$$R^* = R\left(\frac{P_0}{E}\right)^{1/3}; \quad P^* = \frac{\Delta P}{P_0}; \quad I^* = \frac{I^+ c_0}{\left(P_0^2 E\right)^{1/3}}; \quad T^* = T^+ c_0 \left(\frac{P_0}{E}\right)^{1/3}$$

where R is the distance from the center of the explosive charge, m; P_0 is the ambient pressure, Pa; E is the chemical energy released by the reaction, J; ΔP is the overpressure, Pa; c_0 is the speed of sound in air at T_0 and P_0, m/s; I^+ is the impulse from the positive phase, Pa·s; T^+ is the duration of the positive phase, s.

Variables R^*, P^*, I^*, and T^* denote the nondimensional distance, pressure, impulse, and duration of the positive phase, respectively.

As a general rule, blast wave parameters are expressed in terms of the reduced scale either in terms of mass [3, 4] or energy [5, 7, 10] in a manner similar to that used for TNT charts.

For example, the reduced distance λ expressed in m/MJ$^{1/3}$ [7, 10] can be nondimensionalized by stating that

$$R^* = \frac{\lambda}{100}\left(P_0\right)^{1/3}$$

with energy E taken in J and the ambient pressure in Pa. The impulse–energy ratio $I^+/\sqrt[3]{E}$ expressed in bar·ms/MJ$^{1/3}$ can be nondimensionalized by stating that

$$I^* = \frac{I^+}{E^{1/3}} \frac{c_0}{P_0^{2/3}}$$

with pressure taken in Pa, energy in J, and time in s. Similarly, the duration of positive phase $T^+/\sqrt[3]{E}$ expressed in ms/MJ$^{1/3}$ can be nondimensionalized by applying the following relation:

$$T^* = \frac{T^+}{E^{1/3}} c_0 P_0^{2/3} \cdot 10^{-5}.$$

Similar transformations can be applied when the variables are expressed in terms of mass. Nondimensionalization of the variables is then carried out as follows. If the reduced distance is defined as

$$Z^* = \frac{R}{\sqrt[3]{M}},$$

then the nondimensional distance is

$$R^* = Z\left(\frac{P_0}{E_M}\right)^{1/3}$$

with pressure taken in Pa, specific energy E_M in J/kg, whereas impulse $I^+/\sqrt[3]{M}$ (bar·ms/kg$^{1/3}$) and duration of the positive phase $T^+/\sqrt[3]{E}$ (ms/kg$^{1/3}$) are nondimensionalized as

$$I^* = \frac{I^+}{M^{1/3}}\frac{c_0 \cdot 10^5}{P_0^{2/3}E_M^{1/3}}; \quad T^* = \frac{T^+}{M^{1/3}}\left(\frac{P_0}{E_M}\right)^{1/3} c_0 \cdot 10^{-3}$$

where I^+ is taken in bar·ms, c_0 in m/s, P_0 in Pa, and E_M in J/kg.

However, Dewey [5] expresses the reduced distance as

$$R_s = R\left(\frac{P_0}{P_N}\right)^{1/3}\left(\frac{1}{M}\right)^{1/3}$$

where R_s and R are the reduced and real distances; P_0 is the atmospheric pressure measured at the time of explosion; P_N is the pressure at normal temperature and pressure (NTP) conditions (101.325 kPa), and M is the mass of the explosive charge. The effects of explosions of gaseous charges placed at ground level can be compared with those produced by a TNT charge. Figures 2 to 4 present all available results with explosions of hemispherical gas volumes considered as unconfined air explosion by doubling the volume of gaseous mixture. Tables 2 to 4 provide the corresponding polynomial laws.

The evolution of overpressure P^* as a function of distance R^* for a TNT charge represented by TM5-1300 chart can be perfectly superimposed on the one established by Dewey [3]. The TM5-1300 is the standard chart describing the evolution of characteristic parameters of a spherical blast wave propagating in air which has been obtained for the TNT charge located on the ground level or at a certain altitude. The pressure measurements have been performed at ground or at the symmetry axis of the sperical charge. The Dewey's chart was obtained with a hemispherical charge of 1 kg TNT using AirBlast software.

These charts are applicable to situations when a gaseous charge is detonated and the presence of the ground does not interfere with the effects of detonation.

Kogarko *et al.* [4] obtained the results for the overpressure, impulse, and duration of the positive phase for the stoichiometric propane–air mixture initiated by a critical charge of 155 g TNT. Measurement points were located in the region 5–50 radii of the charge.

Brossard *et al.* [5] (or Lannoy [10]) performed AMEDE tests with spherical (positioned at height h) and hemispherical clouds with a volume ranging from 1.6 to 510 m^3 for different stoichiometric mixtures (C_2H_2–air, C_3H_8–air, and C_2H_4–

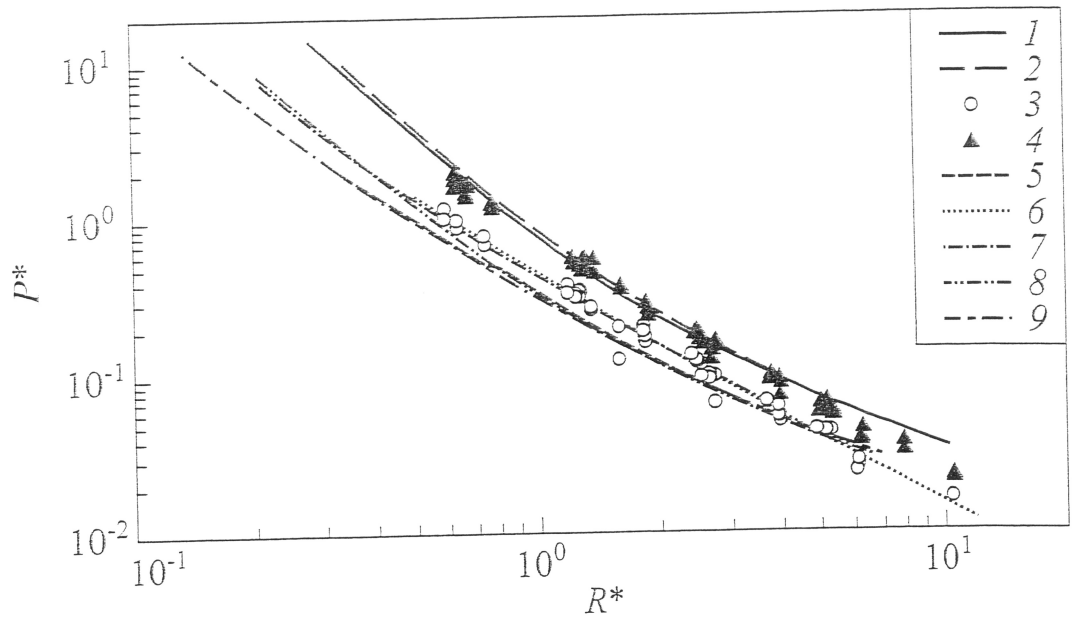

Figure 2 Positive blast pressure vs. distance: *1* — TNT: [11]; *2* — TNT: [3]; *3* — Fraunhofer Institute — Configuration A: $V = 0.77$–7.54 m^3; *4* — Fraunhofer Institute — Configurations B, C, and D: $V = 1.45$–14.33 m^3; *5* — [4]: $V = 10$–15 m^3; *6* — [5]: $V = 1.6$–510 m^3; *7* — [6]: $V = 268$ m^3; *8* — [3]: $V = 14{,}479$ m^3; and *9* — [7]: $V = (0.13\text{–}4.2) \cdot 10^{-3}$ m^3

Table 2 Fitting coefficients in $\ln P^* = A + B \ln R^* + C (\ln R^*)^2 + D (\ln R^*)^3$

Author	A	B	C	D	Range of validity R^*
Fraunhofer Institute — Configuration A	−0.777	−1.6022	0.0502		0.6–10.4
Fraunhofer Institute — Configurations B, C, and D	−0.2549	−1.7379	0.1015		0.6–10.6
Kogarko *et al.* [4]	−1.0972	−1.5223	0.1072		0.3–3.3
Brossard *et al.* [5]	−0.9375	−1.5591	0.1775		0.3–12.0
Dorofeev [6]	−0.8599	−1.5450	0.2003		0.2–3.8
Dewey [3]	−1.1338	−1.8322	0.2984	0.0862	0.2–7.0
Trélat [7]	−1.1599	−1.5160	0.1600		0.13–7.0

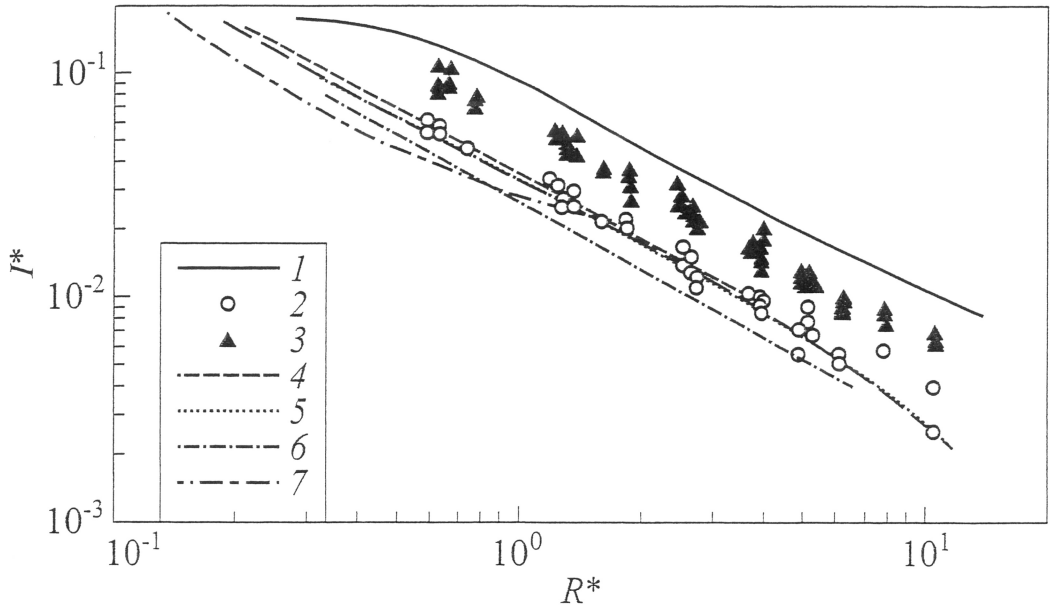

Figure 3 Blast impulse vs. distance: *1* — TNT: [11]; *2* — Fraunhofer Institute — Configuration A: $V = 0.77$–0.54 m^3; *3* — Fraunhofer Institute — Configurations B, C, and D: $V = 1.45$–14.33 m^3; *4* — [4]: $V = 10$–15 m^3; *5* — [5]: $V = 1.6$–510 m^3; *6* — [6]: $V = 268$ m^3; and *7* — [7]: $V = (0.13\text{–}4.2) \cdot 10^{-3}$ m^3

Table 3 Fitting coefficients in $\ln I^* = E + F \ln R^* + G (\ln R^*)^2$

Author	E	F	G	Range of validity R^*
Fraunhofe Institute — Configuration A	−3.3410	−0.9484	−0.0211	0.6–10.4
Fraunhofer Institute — Configurations B, C, and D	−2.8084	−0.9319	−0.0364	0.6–10.6
Kogarko *et al.* [4]	−3.6382	−1.0000		0.3–6.6
Brossard *et al.* [5]	−3.4327	−0.9619	−0.0166	0.3–12.0
Dorofeev [6]	−3.3439	−0.9680	0	0.2–3.8
Trélat [7]	−3.5820	−0.5700	0.1900	0.13–1.9

air). These mixtures were initiated by small charges of solid explosives at the center of volume symmetry. In the case of spherical volumes, their pressure data correspond to the situation without reflections on the ground (thus to radial distances $R \leq h$). Dorofeev *et al.* [1, 6] determined the effect of fuel concentration on blast wave parameters produced by the detonation of stoichiometric and fuel-rich gas mixtures. Propane–air mixtures were contained in hemispherical balloons with a radius of 4 m and volume concentration of propane between 4%

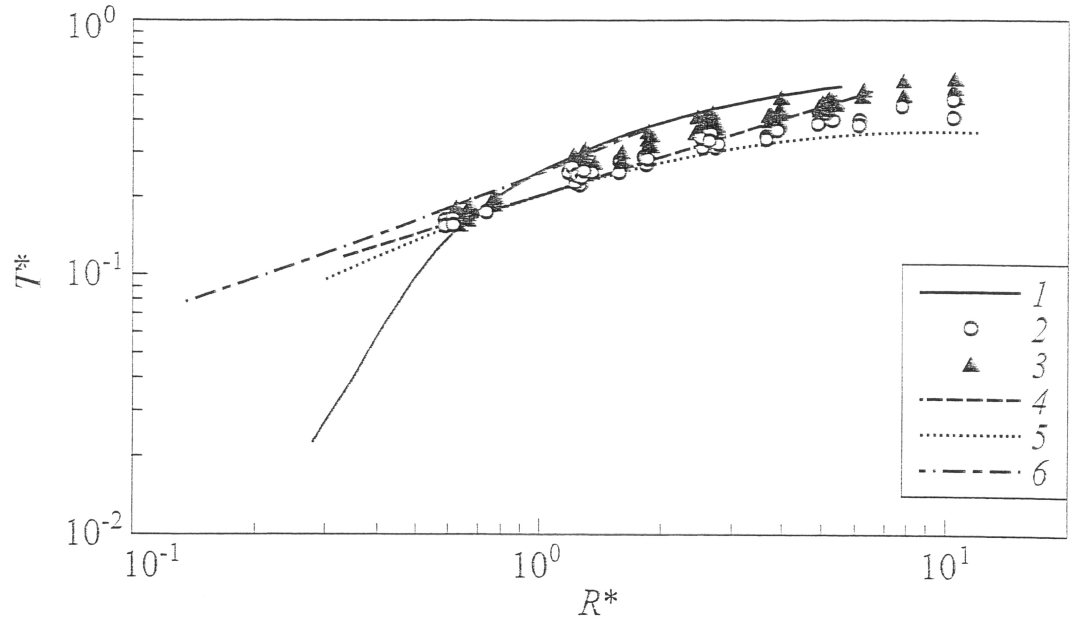

Figure 4 Duration of blast positive phase vs. distance: *1* — TNT: [11]; *2* — Fraunhofer Institute — Configuration A: $V = 0.77$–7.54 m^3; *3* — Fraunhofer Institute — Configurations B, C, and D: $V = 1.45$–14.33 m^3; *4* — [4]: $V = 10$–15 m^3; *5* — [5]: $V = 1.6$–510 m^3; and *6* — [7]: $V = (0.13\text{–}4.2) \cdot 10^{-3}$ m^3

Table 4 Fitting coefficients in $\ln T^* = H + J \ln R^* + K (\ln R^*)^2$

Author	H	J	K	Range of validity R^*
Fraunhofer Institute — Configuration A	−1.5587	0.5406	−0.0916	0.6–10.4
Fraunhofer Institute — Configurations B, C, and D	−1.4584	0.6101	−0.1101	0.6–10.6
Kogarko *et al.* [4]	−1.5936	0.5000		0.3–6.6
Brossard *et al.* [5]	−1.5833	0.5038	−0.1118	0.3–12.0
Trélat [7]	−1.3951	0.6343	0.0290	0.2–1.9

and 7%. The effect of fuel concentration [1] was shown to have no significant effect on blast wave parameters.

In 2005, Dewey analyzed the experiments carried out in the 1950s under the name "FE 567/2a" in Suffield, Canada and "Operation Distant Plain" in the USA. The measurements of the arrival time of the preliminary shock wave produced by the detonation of a charge of stoichiometric propane–oxygen mixture 19,281 kg in total mass were analyzed in order to obtain the dependence of peak overpressure on distance. The distance vs. time dependence was expressed as

$$R = A + Ba_0t + C\ln(1 + a_0T) + D\sqrt{\ln(1 + a_0t)}$$

where A, B, C, and D are the constants; a_0 is the speed of sound in the surrounding air; and P_0 is the ambient pressure at the time of explosion. Differentiation of this relationship gives the Mach number, and the hydrostatic pressure can be then deduced from the Pankine–Hugoniot relations. This results in the following relationship:

$$\ln R_s = E + F\ln P + G(\ln P)^2 + H(\ln P)^3$$

where E, F, G, and H are the fitting coefficients; R_s is the reduced distance, $\mathrm{m/kg^{1/3}}$; and P is the atmospheric pressure.

The differences observed between small- and large-scale experiments in the near field ($R^* < 1$) is explained by the fact that the charge in large-scale tests cannot be considered as a point source in opposite to small charges or TNT explosives.

The results obtained from full-scale tests with hemispherical charges (Fraunhofer Institute, Configuration A) correlate well with those obtained in [3, 5, 6]. The small-scale tests as well as those carried out in [4] are similar but the measured overpressures are lower when compared with other experiments. This is also valid for the evolution of impulse. As to the evolution of the duration of the positive phase, the results are closer, but the small-scale tests give higher results than other tests. The most notable difference with regard to the Fraunhofer Institute experiments is found between the tests conducted at ground level with hemispherical charges (Configuration A) and the tests with spherical charges

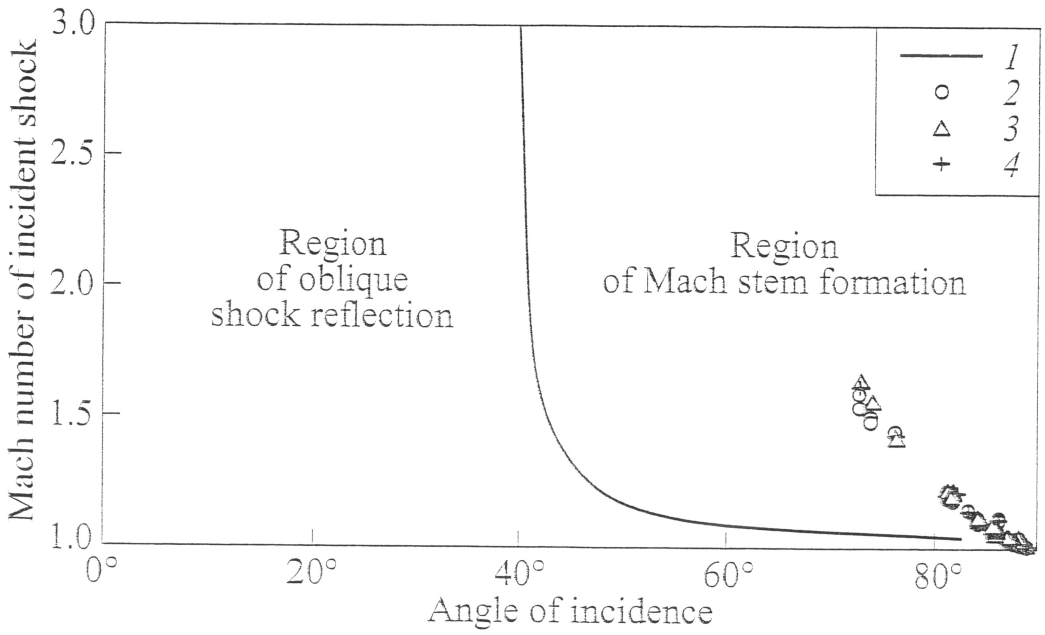

Figure 5 Angle for transition from oblique shock to Mach stem formation: *1* — empirical hyperbolic equation [12]; *2* — Fraunhofer Institute — Configuration B; *3* — Fraunhofer Institute — Configuration C; and *4* — Fraunhofer Institute — Configuration D

(Configurations B, C, and D). Nevertheless, the results for spherical charges correlate well in terms of pressure, impulse, and arrival time, regardless of whether the igniter was placed in the center or at the periphery, so well that it was possible to derive a single correlation. The positive overpressures, impulses, and durations obtained with the spherical charges at ground level (Fraunhofer Institute, Configurations B, C, and D) do not superimpose on those resulting from explosions of hemispherical and spherical charges in the experiments of Kogarko *et al.* [4] and Brossard *et al.* [5]. Configuration A corresponds to free (without reflection) propagation of shock waves. For hemispherical charges or spherical charges at altitude (when the height of burst is higher than the charge radius), the symmetry of shock wave propagation is preserved, whereas for spherical volumes lying on the ground, it is not the case. In Configurations B, C, or D, several reflections from the ground take place which disturb the pressure field. In this case, the type of wave is not known: is it a Mach or regular wave? An analysis shows (Fig. 5) that the wave possesses the configuration of Mach wave which explains why the overpressures are higher.

4 TNT EQUIVALENCY

The data on blast wave parameters have been obtained by a large number of researchers for different explosives. They make it possible to obtain various predictions of blast parameters depending on the source. The most widely used charts are those taken from the manual *Structures to Resist the Effects of Accidental Explosions* for TNT charges. When blast effects for other types of explosive charges should have to be determined, the concept of TNT equivalence is often used.

The TNT equivalence is defined as the ratio of the TNT mass to the mass of the explosive that will produce the same amplitude of blast wave at the same radial distance from the charge using the Sachs and Hopkinson scaling laws. All explosives generate blast waves that have similar characteristics. However, their TNT equivalent can vary with the distance. This means that a single value is not appropriate. Moreover, only few explosives have been tested at the same conditions and it is therefore difficult to estimate the overpressure or other blast wave parameters with a good equivalence.

Esparza [13] based the energy equivalency on the incident pressure as the ratio of the TNT mass to the mass of the explosive in question that gives the same peak overpressure at the same radial distance from the charge. The pressure equivalent for an explosive is thus:

$$E_P = \frac{M_{\mathrm{TNT}}}{M} = \left(\frac{Z}{Z_{\mathrm{TNT}}}\right)^3_{P_{\mathrm{cst}}}$$

where Z is the reduced distance such as $Z = R/M^{1/3}$; R is the distance from the center of the explosive source; and M is the explosive mass. A similar procedure is carried out for the impulse equivalency:

$$E_I = \frac{M_{\text{TNT}}}{M} = \left(\frac{Z}{Z_{\text{TNT}}}\right)^3_{I_{\text{cst}}} .$$

However, even when the impulses stand in relation to the cubic root of the mass, the impulse equivalencies are obtained by sliding the curves over the first bisector. Esparza [13] carried out a study on several condensed explosives (Composition B, PBX-9404, Pentolite, TNT, PBX-9501, and PBX-9502) that present the average pressure equivalency values ranging from 0.9 to 1.7 and in terms of impulse, the equivalency ranges from 0.6 to 1.2.

Dorofeev [6] defined the TNT equivalency of gas charge explosion as the ratio of TNT explosion energy to the energy of gas explosion that has the same value for a given parameter at a fixed distance. Thus, the TNT equivalence must be calculated, on the one hand, based on the distance and, on the other, for each blast wave parameter.

Formby and Wharton [2] and Wharton *et al.* [14] based their calculations of the TNT equivalency on the same procedure employed by Esparza for other types of condensed explosives and determined linear dependencies of TNT equivalency in terms of pressure and impulse on the reduced distance ($\text{m/kg}^{1/3}$).

Ohashi *et al.* [15] and Kleine *et al.* [16] described the procedure for calculating TNT equivalency for charges of several milligrams of silver azide (AgN_3). Their method is based on the availability of the shock radii vs. wave arrival time diagram. These data allow calculating the Mach number of the shock and the peak overpressure depending on the distance as described above (studies by Dewey [3]). The pressure–distance profile is then compared with that for a unit TNT charge in order to determine the equivalency of silver azide in terms of the overpressure and distance from the charge center for the 1-milligram charge of silver azide. The TNT equivalency for silver azide obtained this way varied from 0.3 to 1.4 depending on the distance from the explosion center and was in good agreement with the average value of 0.4 predicted by Baker *et al.* [17] based on the composition of silver azide. Dewey [3] then applied this procedure to significantly larger explosive charges. In this way, an evolution law of energy equivalency was established for the propane–oxygen charge 19.281 kg in mass [3]. The TNT equivalency for pressure was between 0.4 and 0.6 (see Fig. 5).

Figures 6 and 7 show the variations in TNT equivalent for pressure and impulse determined on the basis of pressure (see Fig. 2) and impulse curves (see Fig. 3). The pressure and impulse equivalencies were defined in a similar manner as the ratio of TNT mass, M_{TNT}, to the mass of the explosive charge, M, for a single overpressure value, or by shifting the nondimensional impulses over the first bisector.

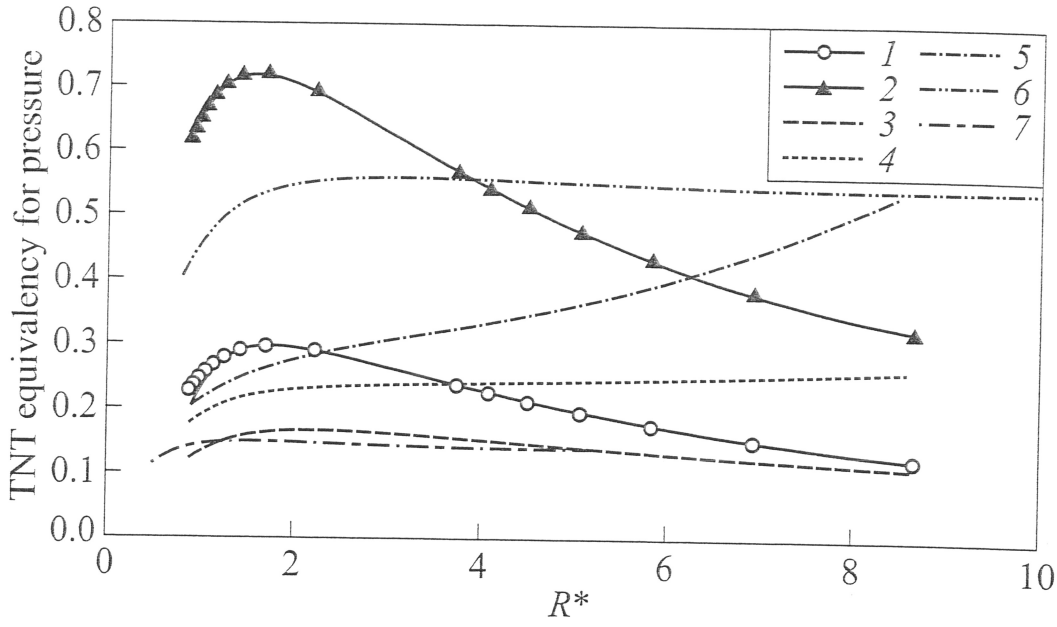

Figure 6 TNT equivalency for positive pressure vs. distance: *1* — Fraunhofer Institute — Configuration A: $V = 0.77$–7.54 m^3; *2* — Fraunhofer Institute — Configurations B, C, and D: $V = 1.45$–14.33 m^3; *3* — [4]: $V = 10$–15 m^3; *4* — [5]: $V = 1.6$–510 m^3; *5* — [6]: $V = 268$ m^3; *6* — [3]: $V = 14{,}479$ m^3; and *7* — [7]: $V = (0.13\text{–}4.2) \cdot 10^{-3}$ m^3

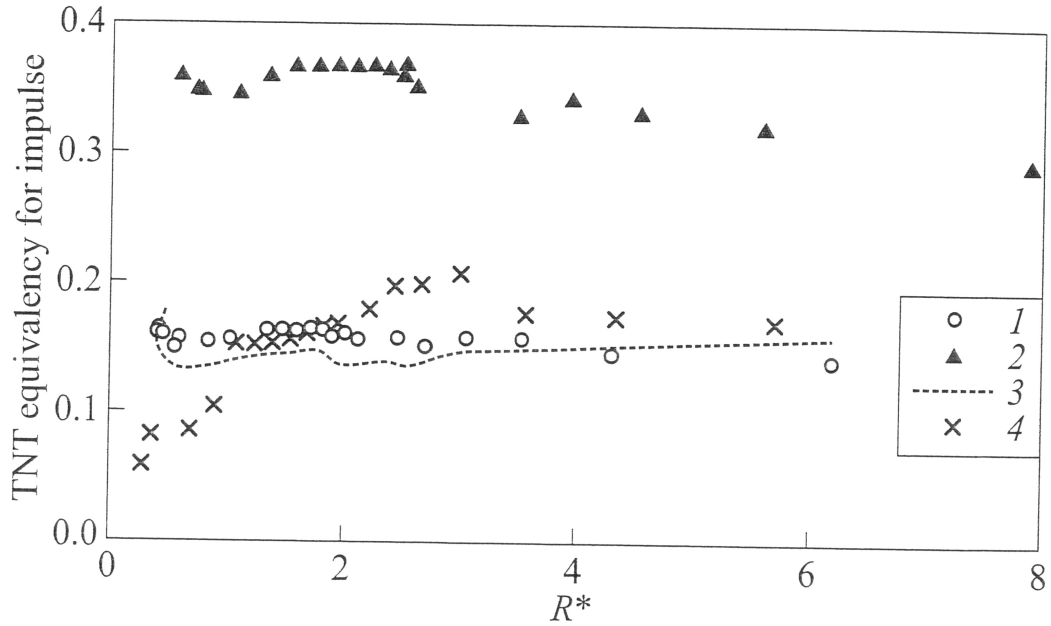

Figure 7 TNT equivalency for positive impulse vs. distance: *1* — Fraunhofer Institute — Configuration A: $V = 0.77$–7.54 m^3; *2* — Fraunhofer Institute — Configurations B, C, and D: $V = 1.45$–14.33 m^3; *3* — [5]: $V = 1.6$–510 m^3; and *4* — [7]: $V = (0.13\text{–}4.2) \cdot 10^{-3}$ m^3

Thus, based on the nondimensional distances, the equivalences for unconfined air explosions (i. e., spherical explosions) are expressed as

$$E - \mathrm{TNT}_P = \frac{M_{\mathrm{TNT}}}{M}; \quad E - \mathrm{TNT}_I = \frac{M_{\mathrm{TNT}}}{M};$$

$$R^* = R\left(\frac{P_0}{E_M M}\right)^{1/3}$$

for the gas explosive charge; and

$$R^*_{\mathrm{TNT}} = R\left(\frac{P_{0,\mathrm{TNT}}}{E_{M,\mathrm{TNT}} M_{\mathrm{TNT}}}\right)^{1/3}$$

for the TNT charge.

Here, E_M and $E_{M,\mathrm{TNT}}$ represent the specific energy of gas explosive and TNT charges, respectively.

Hence, the expression for the TNT-equivalency in terms of pressure is:

$$E - \mathrm{TNT}_P = \frac{M_{\mathrm{TNT}}}{M} = \left(\frac{R^*}{R^*_{\mathrm{TNT}}}\right)^3 \frac{P_{0,\mathrm{TNT}}}{P_0} \frac{E_m}{E_{m,\mathrm{TNT}}}.$$

This formula allows one to take into account the ambient conditions at the time of explosion.

The TNT equivalencies for pressure thus obtained confirm their variation with distance. The dependence of the TNT equivalency for pressure on the nondimensional radial distance exhibits similar shape for the results obtained at small scale (lower than $5 \cdot 10^{-3}$ m^3 [7]), and at large scale (up to 510 m^3 [3–5]). The TNT equivalency increases strongly up to $R^* = 2$ and a mean value can be set for $R^* > 2$. Nevertheless, the dependences obtained by Dorofeev [6] and the results of Fraunhofer ICT do not correlate with the other data. According to [6], the TNT equivalency continues to increase regularly with radius R^* whereas it decreases beyond $R^* = 2$ in the Fraunhofer Institute experiments. The discrepancy between the results and a nonconstant value of the TNT equivalency in terms of pressure depending on the radial distance makes it difficult to estimate the blast effect and the corresponding damage. No universal law seems to exist.

Hence, by plotting all experimental data on blast pressure using the same symbol (Fig. 8), the dispersion of points on the plot allows one to put forward a universal law for gaseous explosions. Of course, for a given radius, the effect on

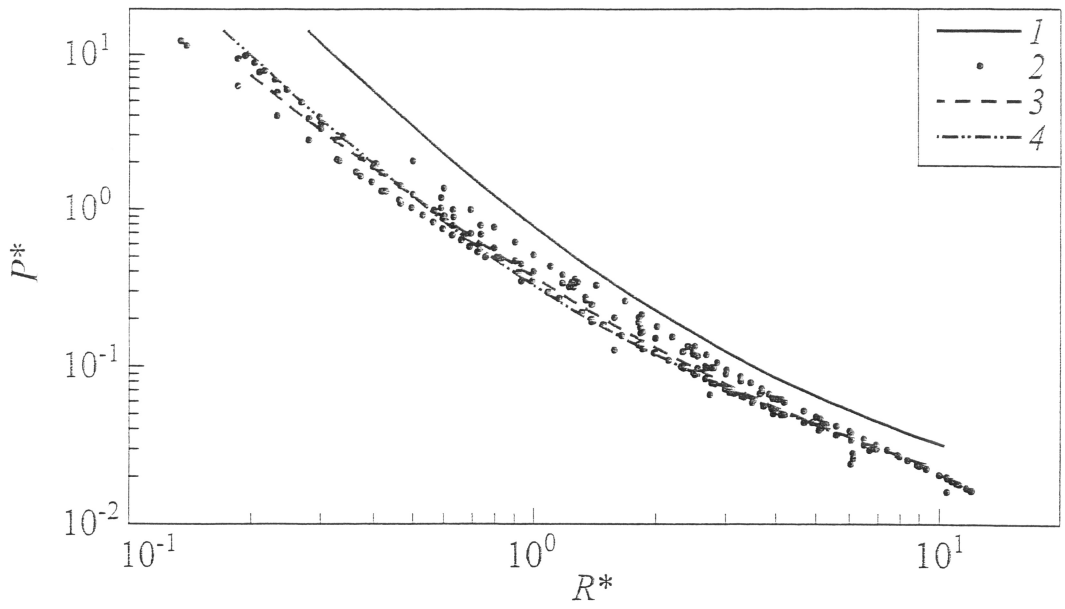

Figure 8 The average dependencies of positive blast pressure vs. distance: *1* — TNT: [11]; *2* — gas, *3* — gas: Eq. (1); and *4* — gas: average TNT equvalency for pressure

the environment in terms of pressure value, or a safe distance for a given pressure level can be considerably different. Nevertheless, the realistic effects produced by the blast wave stay in average in the same range. Hence, by adopting a global approach for an industrial estimation, it is possible to define an universal curve inside the extreme values which is applicable to gas explosions and is expressed by following formula:

$$\ln P^* = -0.9942 - 1.5961 \ln R^* + 0.1656 \left(\ln R^*\right)^2 . \qquad (1)$$

This curve can be well reproduced by assuming a constant value of TNT-equivalency in terms of pressure equal to 0.48. The direct application of this law gives an error of 10%–20% for the near field ($R^* < 1$) and decreases to 5%–10% for the far field (see Fig. 8).

It seems more easy to define a mean value of TNT equivalency in terms of impulse with a rather good accuracy (see Fig. 7) despite of different dependencies on distance deduced for small-scale experiments.

5 CONCLUDING REMARKS

A comparative study of blast wave parameters produced by detonations of gas charges on different scales is presented. All parameters were expressed in a nondimensional form were clearly expressed in analytical form.

Significant differences in TNT equivalent in terms of overpressure were obtained depending on the scale of tests. The need to reject the idea that the TNT

equivalency has a single value regardless of nondimensional distance is very much in line with the works of Dorofeev *et al.* [7] and Dewey [3].

Nevertheless, it can be useful to have an average value to estimate the damage effects in case of a global industrial approach by means of an average TNT-equivalency for pressure or the dependence of blast overpressure vs. radial distance.

REFERENCES

1. Dorofeev, S. B., V. P. Sidorov, and A. E. Dvoinishnikov. 1995. Blast parameters from unconfined gaseous detonations. *20th Symposium (International) on Shock Waves Proceedings*. Pasadena, California, USA. 1:673–78.
2. Formby, S. A., and R. K. Wharton. 1996. Blast characteristics and TNT equivalence values for some commercial explosives detonated at ground level. *J. Hazard. Mater.* 50(2–3):183–98.
3. Dewey, J. M. 2005. The TNT equivalence of an optimum propane–oxygen mixture. *J. Phys. D: Appl. Phys.* 38(23):4245–51.
4. Kogarko, S. M., V. V. Adushkin, and A. G. Lyamin. 1966. An investigation of spherical detonations of gas mixtures. *Int. J. Chem. Eng.* 6(3):93–401.
5. Brossard, J., J. C. Leyer, D. Desbordes, J. P. Saint-Cloud, S. Hendrickx, J. L. Garnier, A. Lannoy, and J. L. Perrot. 1985. Air blast from unconfined gaseous detonations. *9th Colloquium (International) on Dynamics and Reactive Systems Proceedings*. Progress in astronautics and aeronautics ser. Poitiers, France. 94:556–66.
6. Dorofeev, S. B. 1995. Blast effects of confined and unconfined explosions. *20th Symposium (International) on Shock Waves Proceedings*. Pasadena, California, USA. 1:77–86.
7. Trélat, S. 2006. Impact de fortes explosions sur les bâtiments représentatifs d'une installation industrielle. Thèse de Doctorat de l'Université d'Orléans.
8. Behrens, K., and H. Schneider. 1975. Ausbreitungsfunktionen sphärischer Luftstosswellen für den Fall detonierender Äthylen-Luft-Gemische. Fraunhofer ICT.
9. Trélat, S., I. Sochet, B. Autrusson, O. Loiseau, and K. Cheval. 2007. Strong explosion near a parallelepipedic structure. *Shock Waves* 16(4–5):349–57.
10. Lannoy, A. 1984. Analyse des explosions air–hydrocarbure en milieu libre: Etudes déterministe et probabiliste du scénario d'accident. Prévision des effets de suppression. Bulletin Direct. Etudes et Recherches EDF. A4.
11. TM5-1300. 1969. Departments of the Army, the Navy and the Air Force: Structures to resist the effects of accidental explosions. Technical Manual. NAFVAC-P397/AFM88.
12. Kinney, G. F., and K. J. Graham. 1985. *Explosive shocks in air*. 2nd ed. Springer-Verlag.
13. Esparza, E. D. 1986. Blast measurements and equivalency for spherical charges at small scaled distances. *Int. J. Impact Eng.* 4(1):23–40.

14. Wharton, R.K., S.A. Formby, and R. Merrifield. 2000. Airblast TNT equivalence for a range of commercial blasting explosives. *J. Hazard. Mater.* 79(1–2):31–39.
15. Ohashi, K., H. Kleine, and K. Takayama. 2002. Characteristics of blast waves generated by milligram charges. *23rd Symposium (International) on Shock Waves Proceedings*. Ed. F. Lu. Fort Worth, USA. 187–93.
16. Kleine, H., J.M. Dewey, K. Ohashi, T. Mizukaki, and K. Takayama. 2003. Studies of the TNT equivalence of silver azide charges. *Shock Waves* 13(2):123–38.
17. Baker, W.E., P.A. Cox, P.S. Westine, J.J. Kulesz, and R.A. Strehlow. 1983. *Explosion hazards and evaluation*. Amsterdam: Elsevier.