Available online at www.sciencedirect.com

ScienceDirect

Journal of Loss Prevention in the Process Industries 19 (2006) 724–728

Journal of Loss Prevention in the process industries

www.elsevier.com/locate/jlp

Characteristic overpressure–impulse–distance curves for the detonation of explosives, pyrotechnics or unstable substances

Fernando Díaz Alonso[a], Enrique González Ferradás[a,*], Juan Francisco Sánchez Pérez[a], Agustín Miñana Aznar[a], José Ruiz Gimeno[a], Jesús Martínez Alonso[b]

[a]*Grupo de Investigación de Seguridad e Higiene en la Industria, Departamento de Ingeniería Química, Universidad de Murcia, Campus Universitario de Espinardo, 30100 Murcia, Spain*

[b]*Unidad de Protección Civil, Delegación del Gobierno en Madrid, C/ García Paredes, 65. 28010 Madrid, Spain*

Received 24 February 2006; received in revised form 7 June 2006; accepted 8 June 2006

Abstract

A number of models have been proposed to calculate overpressure and impulse from accidental industrial explosions. When the blast is produced by explosives, pyrotechnics or unstable substances, the TNT equivalent model is widely used. From the curves given by this model, data are fitted to obtain equations showing the relationship between overpressure, impulse and distance. These equations, referred to here as *characteristic* curves, can be fitted by means of power equations, which depend on the TNT equivalent mass. *Characteristic* curves allow determination of overpressure and impulse at each distance.

© 2006 Elsevier Ltd. All rights reserved.

Keywords: TNT; Explosion; Overpressure; Impulse; Explosive

1. Introduction

Major hazards concerning the chemical industry are fire, explosion and toxic release. Explosions are very significant in terms of its damage potential, often leading to fatalities and damage to property (Khan & Abbasi, 1999). The blast effects of an explosion are in the form of a shock wave composed of a high-pressure shock front, which expands outward from the centre of the detonation with maximum overpressures decaying with distance (Joint Department of the Army & the Navy and the Air Force, 1990). As regards the magnitude of an explosion, the two most important and dangerous factors are overpressure and impulse (the latter depending on overpressure and positive phase time duration), which are chiefly responsible for damage to humans, structures and environmental elements.

To assess the significance of damage, models are necessary to calculate dangerous magnitudes as a function of distance from the explosion's centre. Most data on explosions and their effects, and many of the methods of estimating these effects, relate to explosives. In particular, the TNT equivalent model is the principal method for calculating the effects of explosions, caused by detonation of either explosives, pyrotechnics or unstable substances (Lees, 1996). The model calculates the TNT equivalent mass W_{TNT}, which is the mass of TNT that would produce the same effects as the amount involved in the explosion. The TNT equivalent mass describes the effect of the explosive at a certain space when it blasts (Rui, Lizhong, Wanghua, Jiacong, & Weicheng, 2002), and can be calculated from the explosive amount W_{exp} and the equivalency factor f (kg TNT/kg explosive substance):

$$W_{TNT} = fW_{exp} \tag{1}$$

Equivalencies for the main explosives and unstable substances can be found in the literature, but it must be taken into account that TNT equivalences often vary with distance, as shown by different bibliographical sources (Conrath, Krauthammer, Marchand, & Mlakar, 1999; Formby & Wharton (1996); Joint Department of the Army

*Corresponding author. Tel.: +34 968 36 73 64, +34 968 36 39 36; fax: +34 968 36 41 48.

E-mail address: ferradas@um.es (E. González Ferradás).

0950-4230/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jlp.2006.06.001

Nomenclature

a	Parameter used in fitted overpressure equation Eq. (11)	P_s	Side-on overpressure (Pa)
b	Exponent of the fitted overpressure equation Eq. (11)	W_{exp}	Mass of explosive substance (kg)
f	Equivalency factor (kg TNT/kg explosive)	W_{TNT}	TNT equivalent mass (kg)
i	Impulse (Pa s)	z	Distance to the explosion's centre (m)
i_{TNT}	Scaled impulse (Pa s/kg$^{1/3}$)	z'	Scaled distance (m/kg$^{1/3}$)
		α	Parameter used in characteristic equation Eq. (8)
		β	Exponent of the characteristic equation Eq. (8)

& the Navy and the Air Force, 1990; Wharton, Formby, & Merrifield, 2000).

Once W_{TNT} has been determined, the scaled distance z' (m/kg$^{1/3}$) can be calculated from the distance in metres z to the explosion's origin, by means of Eq. (2).

$$z' = z/W_{TNT}^{1/3} \quad (2)$$

When the TNT equivalent mass and the scaled distance are calculated, Figs. 1 and 2 can be applied. They show side-on overpressure (P_s, Pa) vs. scaled distance (z', m/kg$^{1/3}$) and scaled impulse (i_{TNT}, Pa s/kg$^{1/3}$) vs. scaled distance (z', m/kg$^{1/3}$) profiles, respectively. These curves have been obtained from hemispherical charges of TNT at ground level and can be used to predict overpressure and impulse produced by different masses of explosive at any distance from the explosion centre and at any altitude, not only at sea level (I. Chem. E (Institution of Chemical Engineers (1994)).

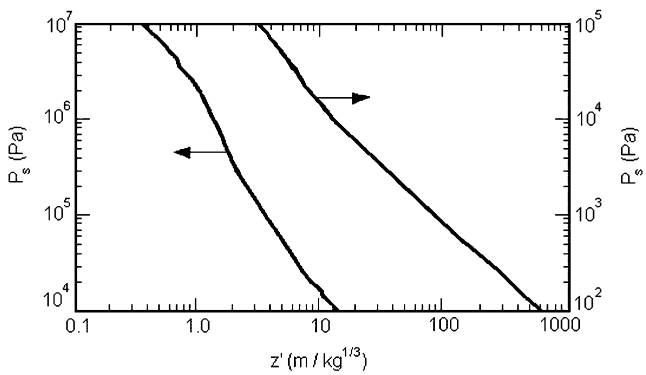

Fig. 1. Side-on overpressure vs. scaled distance for the TNT equivalent model (I.Chem.E, 1994).

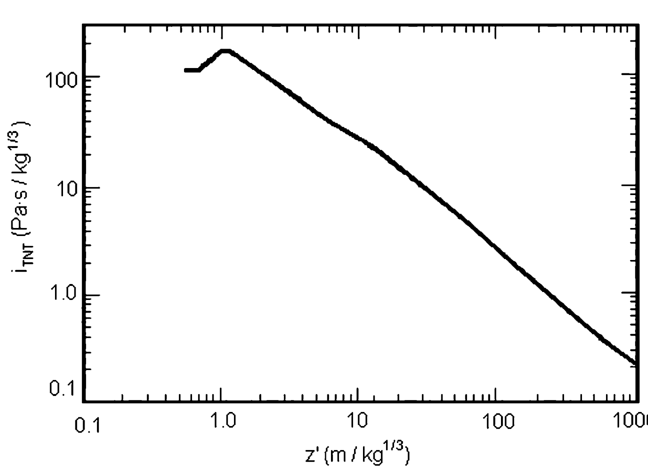

Fig. 2. Scaled impulse vs. scaled distance for the TNT equivalent model (I.Chem.E, 1994).

From the scaled impulse obtained from Fig. 2, the wave's mechanical impulse (i, Pa s) can be calculated as

$$i = i_{TNT} W_{TNT}^{1/3}. \quad (3)$$

2. Characteristic overpressure–impulse–distance curves for the detonation of explosives, pyrotechnics or unstable substances

In every explosion it is possible to obtain the overpressure–impulse–distance relationship, called here the 'characteristic curve'.

Fig. 3 shows graphically the meaning for the so-called *characteristic curve*, traced from the shock wave's overpressure–distance and impulse–distance profiles (taken from Figs. 1 and 2, respectively). Distances to the

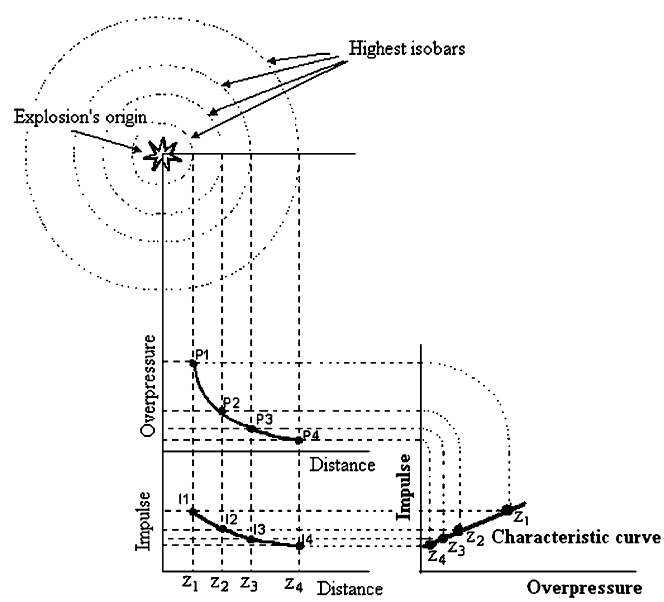

Fig. 3. Characteristic curve of an explosion obtained from overpressure and impulse profiles.

Table 1
Fitted overpressure vs. z' and scaled impulse vs. z' equations (from Figs. 1 and 2)

Interval for z'	Interval for P_s (Pa)	Overpressure equation	Scaled impulse equation
$1 \leqslant z' < 10$	$1.13 \times 10^6 \geqslant P_s \geqslant 11{,}000$	$P_s = 1.13 \times 10^6\ z'^{(-2.01)}$ (4)	$i_{TNT} = 203\ z'^{(-0.91)}$ (5)
$10 \leqslant z' \leqslant 200$	$11{,}000 \geqslant P_s \geqslant 400$	$P_s = 1.83 \times 10^5\ z'^{(-1.16)}$ (6)	$i_{TNT} = 335\ z'^{(-1.06)}$ (7)

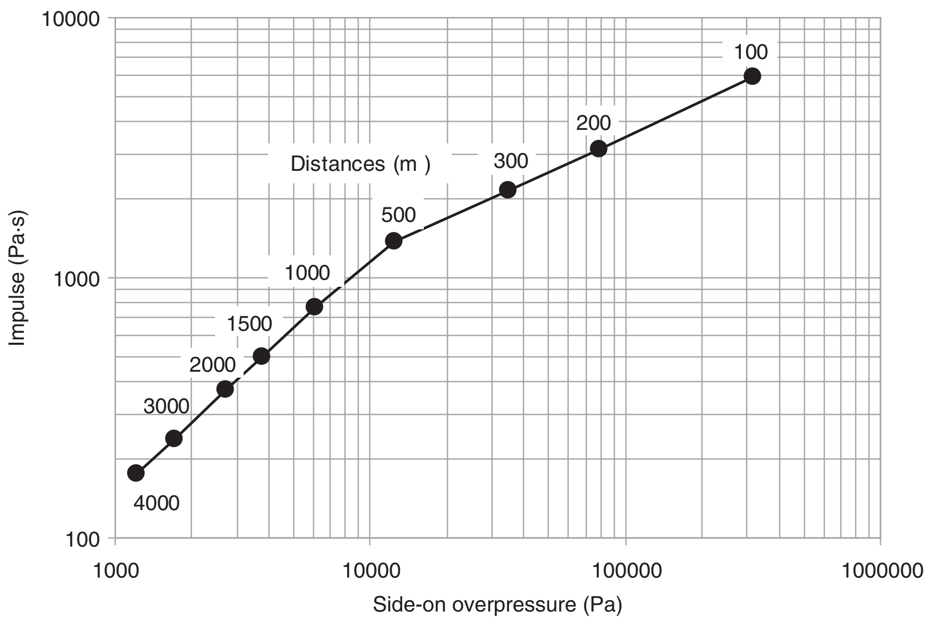

Fig. 4. *Characteristic* curve for a 150-ton TNT equivalent explosion, obtained with the TNT equivalent method.

explosion's centre ($z_1, z_2, \ldots, z_n$) can also be included, to display all the information in the same diagram.

Nevertheless, it is not necessary to draw the overpressure and impulse profiles to obtain the characteristic curves, because they can also be obtained analytically. To perform this operation, the relationships P_s vs. z' and i_{TNT} vs. z' (from Figs. 1 and 2, respectively) are fitted using power equations. To obtain good correlations, each curve is divided into two intervals, as shown in Table 1.

3. Results and discussion

From the corresponding overpressure and impulse equations, depending on the interval, and using Eq. (3), the *characteristic* equations are obtained. They have the following general form .

$$i = \alpha W_{TNT}^{1/3} P_s^{\beta}, \tag{8}$$

where α and β depend on the selected interval.

From Eqs. (3)–(5), the following *characteristic* equation is calculated for the interval $1 \leqslant z' < 10$.

$$i = 3.7 \times 10^{-1} W_{TNT}^{1/3} P_s^{0.45}. \tag{9}$$

In the same way, for the interval $10 \leqslant z' \leqslant 200$, the following *characteristic* equation is obtained.

$$i = 5.2 \times 10^{-3} W_{TNT}^{1/3} P_s^{0.91}. \tag{10}$$

Once the general form of the *characteristic* equations has been obtained, they must be represented in an overpressure–impulse diagram. For example, the characteristic curve for a 150-tons TNT equivalent explosion is represented—similar to that which occurred in Toulouse in 2001 (Carol, 2002). Distance to the explosion's origin is added, obtained by means of Eqs. (2) and (4) or (6), depending on the interval. The result is shown in Fig. 4. It must be taken into account that it is often difficult to determine how much material has participated in an accident and which is the TNT equivalent amount from observed damage. Kersten and Mak (2004) stated that nearly 300 tons ammonium nitrate participated in the explosion (equivalent to 30–40 tons TNT) although they recognize that, in later reports, quantities as high as 400 tons ammonium nitrate are mentioned. Regarding the TNT equivalent amount in Toulouse, quantities ranging from 15 to 200 tons are mentioned by Dechy and Mouilleau (2004). As stated in that paper, the methodologies used for TNT equivalent estimate are in general not so accurate and enable estimate with a range of uncertainty of one order of magnitude. Furthermore, in the case of non-ideal explosions (pyrotechnics or unstable substances), several detonations or deflagrations may be observed in the same accident. Hence, the determination of the TNT equivalent is often complicated and it must be done taking into account particular conditions (Contestabile, Augsten, Jones, & Craig, 1990; Mackenzie & Merrifield, 1997; Merrifield, 2001). The model may be better applicable to emergency planning, where an accident scenario must be supposed and a consequence analysis performed, taking into account that the incertitude will be lower at greater distances.

It can be deduced from Eq. (8) that, for each interval, the relationship between overpressure and impulse depends only on the TNT equivalent mass. The greater the TNT equivalent mass, the higher the impulse for the same overpressure. It can also be deduced from Eq. (8) that parameter β, which is the slope of the *characteristic* curve in a log–log diagram, is constant for each interval. This means that *characteristic* curves are parallel lines whose position depends on the TNT equivalent mass. If the points corresponding to the same distance on different *characteristic* curves are joined, the *iso-distance* lines are obtained. To obtain the equations of these *iso-distance* lines for each interval, the overpressure fitted equation for that interval is taken, whose general form is

$$P_s = az'^{(b)}. \tag{11}$$

By means of Eq. (2), we have

$$P_s = a[z/W_{TNT}^{1/3}]^{(b)}. \tag{12}$$

Finding $W_{TNT}^{1/3}$ from Eq. (12) and substituting it into the corresponding *characteristic* equation Eq. (8), we have

$$i = \alpha a^{1/b} z P_s^{(\beta - 1/b)}. \tag{13}$$

If the distance z is set at a constant value, the relationship between overpressure and impulse for that distance is obtained, which is the *iso-distance* equation. Introducing the constant values (a, b, α and β) for each interval, plotting the *characteristic* curves for different W_{TNT} values (black lines) in the same diagram and tracing the lines that join the same distances (*iso-distances*, represented by grey lines), the curves in Fig. 5 are obtained. These plots allow a quick and simplified determination of overpressure and impulse at each distance for an explosion whose TNT equivalent mass is known.

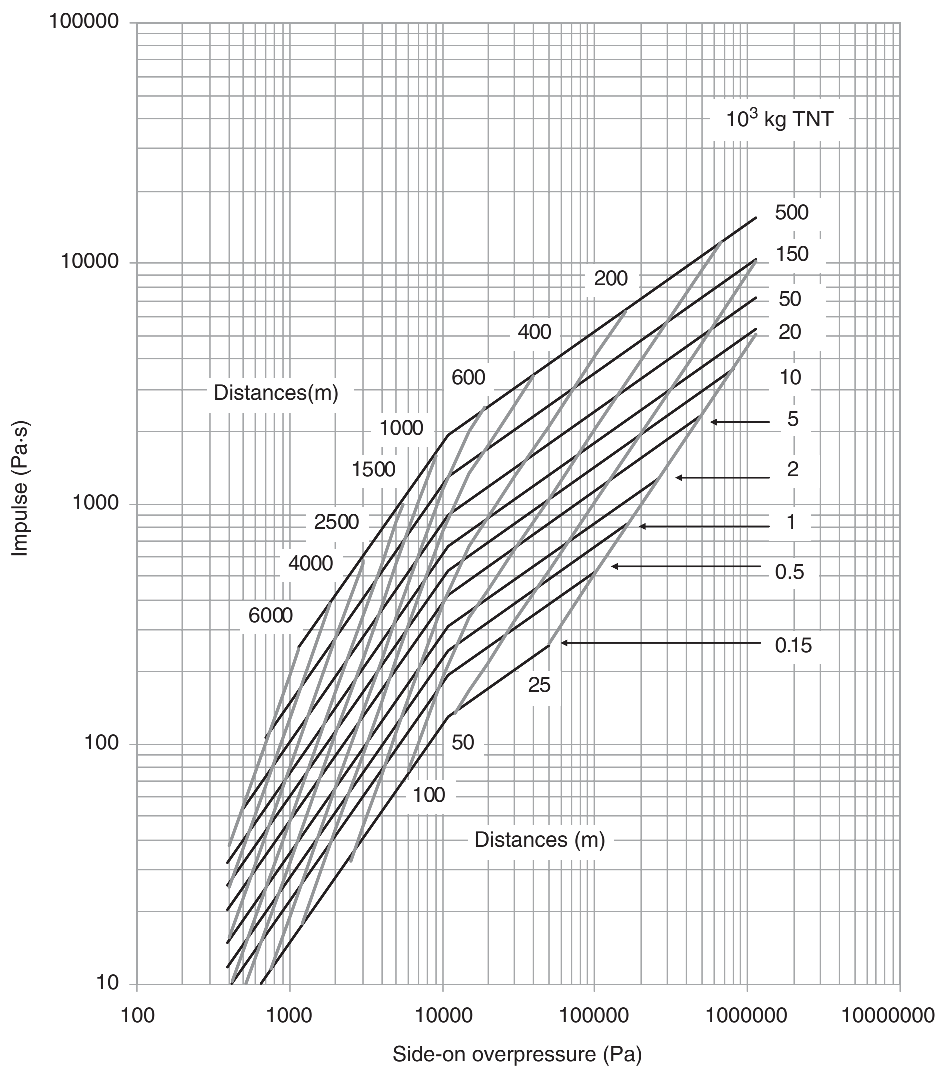

Fig. 5. *Characteristic* curves from detonation of different TNT amounts, using TNT equivalent model.

4. Conclusion

When an industrial accident is caused by explosives, pyrotechnics or unstable substances, the TNT equivalent model is often used to calculate overpressure and impulse from the TNT equivalent mass. From this model, relationship between overpressure and impulse is obtained, depending on the TNT equivalent mass. Here, they are referred to as *characteristic* curves and, if represented in the same diagram, allow the determination of overpressure and impulse at each distance. Using *characteristic* curves simplifies the approach, as both overpressure and impulse can be determined in one step, avoiding any calculation of scaled magnitudes. This model, based on characteristic curves, allows an overview of the evolution and relationship of all variables involved in the detonation of explosives, pyrotechnics or unstable substances. Furthermore, this methodology provides a good tool for consequence analysis. In summary, using this new methodology, simulation of explosions is simpler and faster.

References

Carol, S. (2002). *Estudio del accidente ocurrido en Toulouse el 21 de Septiembre de 2001. Study of the accident happened in Toulouse the 21th September 2001*. Asociación para la prevención de Accidentes (APA) No. 159. pp. 8–17.

Conrath, E., Krauthammer, T., Marchand, K. A., & Mlakar, P. F. (1999). *Structural design for physical security (state of the practice)*. Reston, VA: Task Committee, Structural Engineering Institute, American Society of Civil Engineers (ASCE).

Contestabile, E., Augsten, R. A., Jones, D. E. G., & Craig, T. R. (1990). *The TNT Equivalent of fireworks report shells*. Canadian Explosives Research Laboratory, MRL 90-029 (OPJ), April 1990.

Dechy, N., & Mouilleau, Y. (2004). Damages of the Toulouse disaster, 21st September 2001. Loss prevention and safety promotion in the process industries, 31 May–3 June, 2004. In: 11th international symposium on loss prevention. Praha Congress Centre.

Formby, S. A., & Wharton, R. K. (1996). Blast characteristics and TNT equivalence values for some commercial explosives detonated at ground level. *Journal of Hazardous Materials*(50), 183–198.

I. Chem. E (Institution of Chemical Engineers). (1994). *Explosions in the Process Industries,* Major Hazards Monograph, IChemE.

Joint Department of the Army, the Navy and the Air Force. (1990). *Structures to resist the effects of accidental explosions*. TM 5-1300/ NAVFAC P-397/AFR 88-22, Washington, DC: US Government Printing Office.

Kersten, R. J. A., & Mak, W. A. (2004). Explosion hazards of ammonium nitrate, how to assess the risks? In: *International symposium on safety in the manufacture, use, transport and disposal of hazardous materials.* 10–12 March 2004, Tokyo.

Khan, F. I., & Abbasi, S. A. (1999). Major accidents in process industries and an analysis of causes and consequences. *Journal of Loss Prevention in the Process Industries*, *12*, 361–378.

Lees, F. P. (1996). *Loss prevention in the process industries* (2nd ed.). London: Butterworth-Heinemann.

Mackenzie, J., & Merrifield, R., (1997) Methodology for estimating the explosion yield of incidents involving conventional and improvised explosives. In: *Eighth International Symposium on the Effects of Interaction of Munitions with Structures*, Washington DC, USA, April 1997.

Merrifield, R. (2001). Hazards associated with the storage of fireworks. *Journal of Pyrotechnics*(14).

Rui, H., Lizhong, Y., Wanghua, C., Jiacong, L., & Weicheng, F. (2002). Evaluation of the power of the distributed blast type explosive. *Journal of Loss Prevention in the Process Industries*, *15*, 323–327.

Wharton, R. K., Formby, S. A., & Merrifield, R. (2000). Airblast TNT equivalence for a range of commercial blasting explosives. *Journal of Hazardous Materials*, *A79*, 31–39.