

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

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## 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.

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## 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):

$$W_{TNT} = fW_{exp} \quad (1)$$

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

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

$$z' = z / W_{TNT}^{1/3} \tag{2}$$

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)).

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

$$i = i_{TNT} W_{TNT}^{1/3} \tag{3}$$

### 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

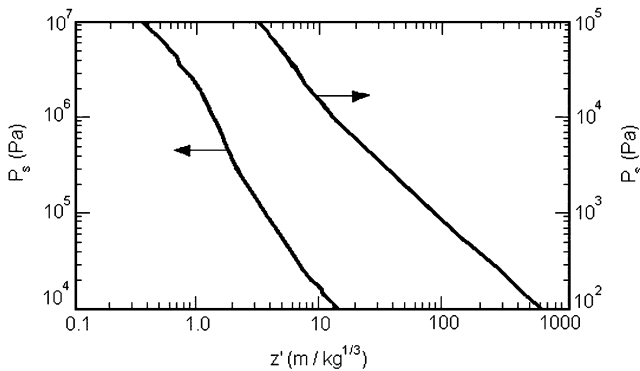


Fig. 1. Side-on overpressure vs. scaled distance for the TNT equivalent model (I.Chem.E, 1994).

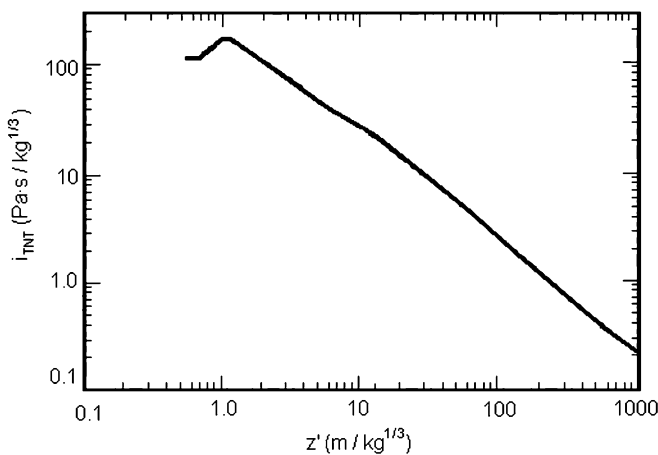


Fig. 2. Scaled impulse vs. scaled distance for the TNT equivalent model (I.Chem.E, 1994).

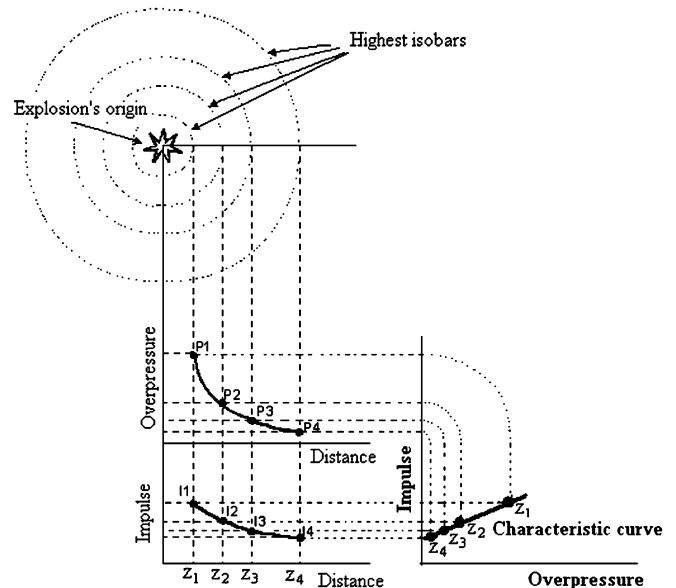


Fig. 3. Characteristic curve of an explosion obtained from overpressure and impulse profiles.

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
$1 \leq z' < 10$	$1.13 \times 10^6 \geq P_s \geq 11,000$	$P_s = 1.13 \times 10^6 z'^{(-2.01)}$ (4)	$i_{TNT} = 203 z'^{(-0.91)}$ (5)
$10 \leq z' \leq 200$	$11,000 \geq P_s \geq 400$	$P_s = 1.83 \times 10^5 z'^{(-1.16)}$ (6)	$i_{TNT} = 335 z'^{(-1.06)}$ (7)

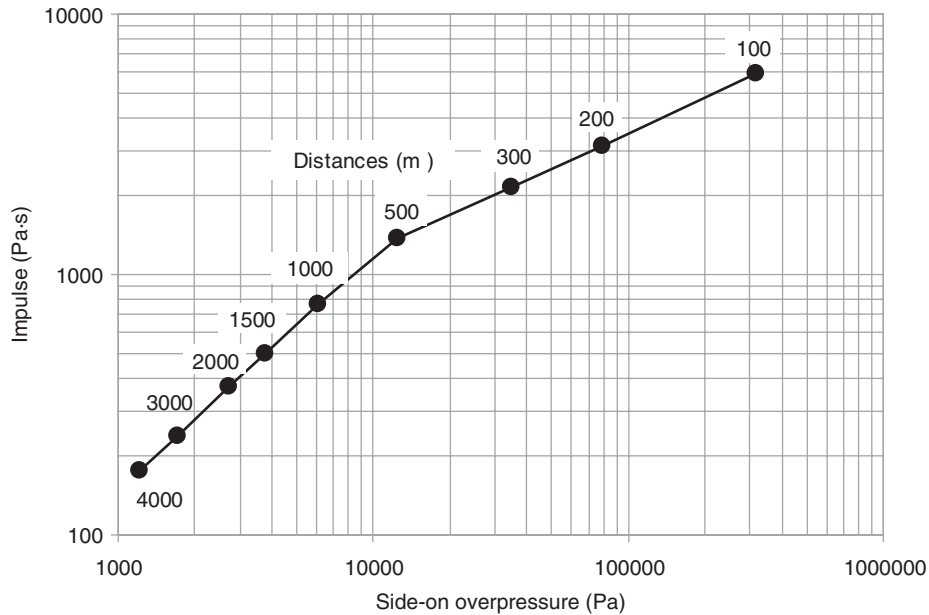


Fig. 4. Characteristic curve for a 150-ton TNT equivalent explosion, obtained with the TNT equivalent method.

explosion’s centre ( $z_1, z_2, \dots, z_n$ ) 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  $\alpha$  and  $\beta$  depend on the selected interval.

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

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

In the same way, for the interval  $10 \leq z' \leq 200$ , 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 uncertainty 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  $\beta$ , 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 ( $a$ ,  $b$ ,  $\alpha$  and  $\beta$ ) 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.

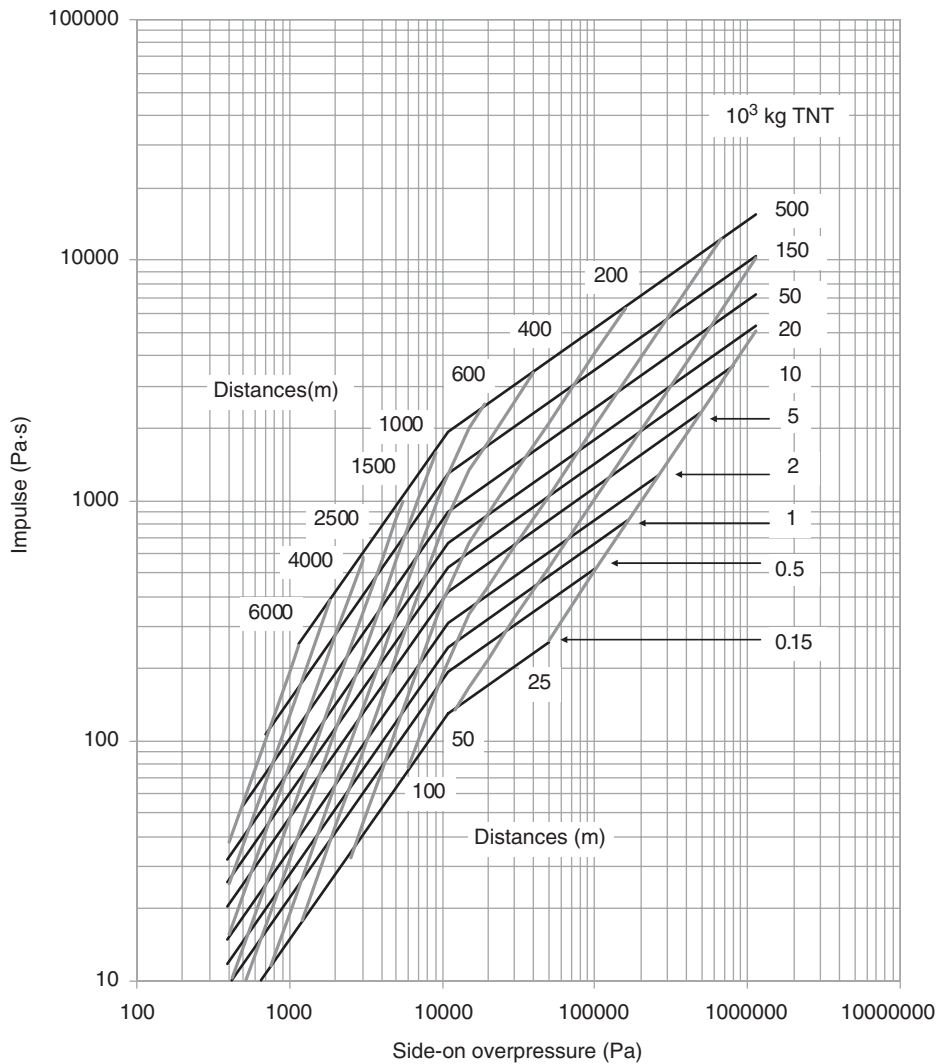


Fig. 5. Characteristic curves from detonation of different TNT amounts, using TNT equivalent model.

#### 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.

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