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Consequence analysis to determine the damage to humans from vapour cloud explosions using *characteristic curves*

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Abstract

The aim of this paper is to provide a methodology to facilitate consequence analysis for vapour cloud explosions (VCE). Firstly, the main PROBIT equations to evaluate direct damage on humans from those accidents (eardrum rupture, death due to skull fracture, death due to whole body impact and lung damage) are discussed and the most suitable ones are selected. Secondly, a new methodology is developed to relate characteristic overpressure-impulse-distance curves for VCE, obtained in a previous paper (F. Diaz Alonso et al., Characteristic overpressure–impulse–distance curves for vapour cloud explosions using the TNO Multi-Energy model, J. Hazard. Mater. A137 (2006) 734–741) with the selected PROBIT equations. This methodology allows the determination of damage as a function of distance to the accident's origin in only one step, using explosion energy and VCE Multi-Energy charge strength as input parameters.

Keywords: Vapour cloud explosion VCE; Overpressure; Impulse; Damage; Consequence analysis

1. Introduction

Amongst the different type of explosions, vapour cloud explosions (VCE) are one of the most serious hazards in refining and petrochemical industries [2]. Since the 1970s, when several devastating vapour cloud explosions occurred, a considerable degree of attention and research effort has been focused on this subject [3]. The main models for determining the extent of the danger from explosions aim to calculate the overpressure and impulse, which are the parameters responsible for causing damage. In particular, these magnitudes are calculated in order to perform consequence analysis [4–9]. In a previous paper [1] the methodology to build the characteristic overpressure–impulse–distance curves for VCE was presented, as well as the way to use them. The characteristic curves for VCE with a Multi-Energy charge strength (hereinafter charge strength) of 10 are shown in Fig. 1. These diagrams show an overview of the evolution of the variables involved in these accidents. The diagrams for the rest of charge strengths (1–9) can be found in [1]. In Fig. 1 the characteristic curve from the Flixborough explosion is highlighted, since this is used in this paper as an example of application of the proposed methodology.

Until the characteristic curves were presented, to carry out a consequence analysis it was necessary to run a model (usually the TNO Multi-Energy for VCE [10]) once for each selected distance from the explosion's origin in order to obtain the overpressure and impulse. Then it was necessary to take into account some damage criteria to determine which consequences would be expected at those distances. Damage criteria can be taken either from tables that relate some overpressure–impulse combinations to the expected degree of damage [11], or from the PROBIT equations [12], which relate the parameters of the explosion to the percentage of the exposed population that will suffer a certain degree of damage. PROBIT equations are used in this paper, since they are the most widely used methodology to determine damage [13]. The methodology proposed here consists in the combination of PROBIT equations corresponding to different damage levels with the explosion's characteristic

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curve. This allows direct determination of possible damage as a function of distance to the explosion's origin.

It must be taken into account that VCE produce two dangerous phenomena: pressure wave and thermal effects. In this paper only damage due to pressure wave is considered. That is why PROBIT equations (and thus, also characteristic curves and fundamental equations used in this paper) are only applied for distances exceeding the maximum flame distance, since inside this the release of thermal energy is so high that mortality due to thermal effects is expected to reach 100%. The maximum flame distance can be estimated with a conservative criterion considering the distance where the concentration equals the half of the lower flammable limit.

Nomenclature

a	Fitting parameter used in ref. [1] to build the characteristic curves (Pa)
b	Fitting parameter used in ref. [1] to build the characteristic curves (dimensionless)
c	Fitting parameter used in ref. [1] to build the characteristic curves (Pa s)
d	Fitting parameter used in ref. [1] to build the characteristic curves (dimensionless)
i	Impulse (Pa s)
z	Distance to the explosion's centre (m)
A	Constant in PROBIT equations (dimensionless)
B	Constant in PROBIT equations (dimensionless)
D_n	Deviation of affected population (%)
E_{exp}	Explosion energy (J)
F	Parameter included in the ln of PROBIT equations. It reflects the contribution of dangerous magnitudes to damage (different dimensions depending on the type of damage)
F'	Parameter used to develop fundamental equations. It's a modified F factor, since it does not depend on dangerous magnitudes (P_s or i), but on distance and explosion energy (different dimensions depending on the type of damage)
N	Multi-Energy charge strength (dimensionless)
P	Constant used to obtain a modified PROBIT expression (dimensionless)
P_{ef}	Effective overpressure (Pa), which is the actual pressure exerted on human beings dependent on the position of these with regard to the wave
P_s	Side-on overpressure (Pa)
Q	Constant used to obtain a modified PROBIT expression (dimensionless)
R	Percentage of damage (%)
Y	PROBIT (dimensionless)

2. Description of PROBIT equations

Firstly, a comparison of different published PROBIT equations is performed and the most suitable ones are selected.

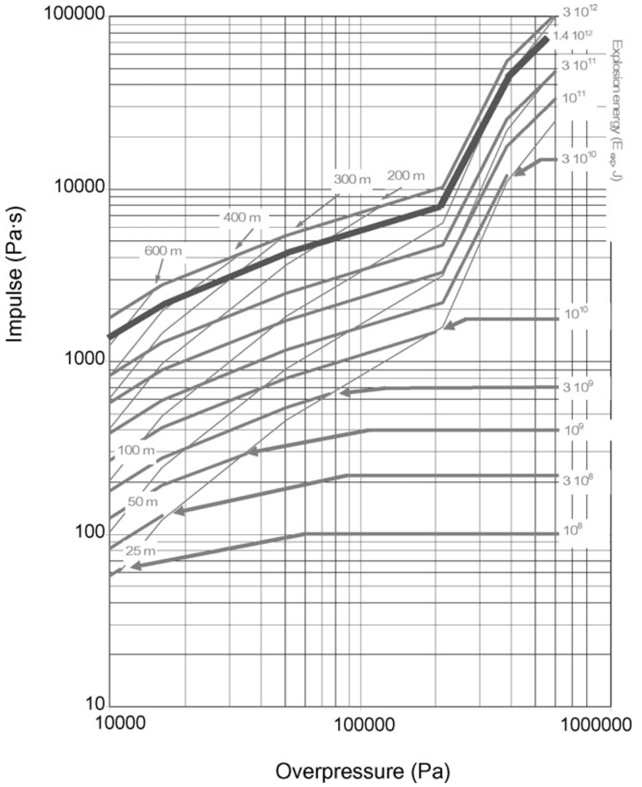

Fig. 1. Characteristic overpressure–impulse–distance curves for VCE with a Multi-Energy charge strength of 10. The Flixborough VCE (United Kingdom, 1974) is highlighted in bold.

PROBIT equations (Y) are in the general form shown by Eq. (1).

$$Y = A + B \cdot \ln F = A + B \cdot \ln[f(P_s, i)] \tag{1}$$

where A and B are constants depending on the type of damage, and F is a function of the dangerous magnitudes (in the case of explosions F is the overpressure -P_s- or a combination of overpressure and impulse -i-).

PROBIT equations shown in Table 1 are those found in the literature for different types of damage from explosions on human outdoors.

PROBIT equations for eardrum rupture – Eqs. (2) and (3) from Table 1 – only depend on the overpressure, and their suitability is evaluated in Table 2. To perform this operation, the deviations obtained from both of them are evaluated with regard to the data cited by Lees [11] from real explosions D (%). In Table 2, R is the percentage of people suffering eardrum rupture at the indicated overpressure (as shown by several authors in ref. [11]). R_1 and R_2 are the percentages calculated by means of each PROBIT equation in the same conditions (using the table published by [13] showing the relationship between PROBIT and percentage of affected population, which is valid for every PROBIT equation). D_n ($n = 1$ or 2) is the deviation, calculated as

$$D_n = R_n - R \tag{10}$$

Nevertheless, R–Y data from ref. [13] have been fitted by means of Eq. (11), valid for R values between 5% and 95% of

Table 1
PROBIT equations for different types of damage from explosions on human outdoors

Type of damage	PROBIT equations		References
Eardrum rupture	$Y_1 = -12.6 + 1.524 \ln P_s$	(2)	[11,13,14]
	$Y_2 = -15.6 + 1.93 \ln P_s$	(3)	[11,13]
Death due to head impact	$Y_3 = 5 - 8.49 \ln \left(\frac{2430}{P_S} + \frac{4 \times 10^8}{P_S \times i} \right)$	(4)	[11,13–15]
Death due to whole body impact	$Y_4 = 5 - 2.44 \ln \left(\frac{7.38 \times 10^3}{P_S} + \frac{1.3 \times 10^9}{P_S \times i} \right)$	(5)	[11,13–16]
	$Y_5 = 5 - 4.82 \ln \frac{40267}{i}$	(6)	[16]
Death due to lung haemorrhage	$Y_6 = 5 - 5.74 \ln \left(\frac{4.2 \times 10^5}{P_{ef}} + \frac{1694}{i} \right)$	(7)	[11,13–16]
	$Y_7 = 5 - 6.6 \ln \left(\frac{620550}{P_S} + \frac{2069}{i} \right)$	(8)	[16]
	$Y_8 = -77.1 + 6.91 \ln P_s$	(9)	[11]

Table 2
Comparison between the two most widely referenced PROBIT equations for eardrum rupture

P_s (Pa)	R (%) from real data in ref. [11]	Eq. (2)			Eq. (3)		
		Referenced in [11,13,14]			Referenced in [11,13]		
		Y_1	R_1 (%)	D_1 (%)	Y_2	R_2 (%)	D_2 (%)
34500	Threshold 1–5	3.32	5	–	4.56	33	–
101300	50	4.97	49	−1	6.64	95	+45
116500	52	5.18	57	+5	6.91	97	+45

Data from real explosions obtained from ref. [11] have been used to perform this comparison

affected population.

$$R = -3.25 \cdot Y^3 + 48.76 \cdot Y^2 - 206.60 \cdot Y + 270.35 \qquad (11)$$

The data from Table 2 show that Eq. (2) fits better to real data than Eq. (3). Moreover Eq. (2) is more widely referenced than Eq. (3). For both reasons, Eq. (2) has been selected in this paper.

In Table 1, Eq. (4) is the only PROBIT equation found for death due to skull fracture and this is selected in this paper.

No real data have been found to compare the suitability of PROBIT equations for death due to whole body impact—Eqs. (5) and (6) from Table 1. Furthermore, the comparison of both PROBIT equations is difficult due to the different parameters they depend on. Thus, Eq. (5) depends on overpressure and impulse whereas Eq. (6) only depends on impulse. Nevertheless, in Table 3 the data obtained from the application of Eq. (5) and Eq. (6) to the VCE of Flixborough are included. It can be deduced that data provided by Eq. (6) are not applicable to real situations, since the percentage of affected population decreases from 95 to 5% in only six meters. On the contrary, Eq. (5) provides more realistic results. Moreover, Eq. (5) is more widely referenced that Eq. (6). For both reasons, Eq. (5) has been selected in this paper.

For death due to lung haemorrhage, Eqs. (7)–(9) from Table 1 are those published in the literature. As it has been shown by several studies [11], mortality due to lung damage depends on overpressure and impulse, since different results have been achieved for short- and long-duration waves. Thus, Eq. (9) is rejected, since it does not allow the contribution of impulse to be taken into account. As regards Eqs. (7) and (8), it has been proven [11] that not only incident overpressure is important to determine lung damage, but also body's position. The only PROBIT equation that allows this contribution to be

Table 3
Comparison of the calculated distances by means of Eqs. (5) and (6) for 5, 50 and 95% of mortality due to whole body impact in the Flixborough's explosion

R (%) Mortality due to whole body impact	Y (from Eq. (11))	Eq. (5) (Y_4[a])			Eq. (6) (Y_5)	
		P_s (Pa)	i (Pa s)	z (m)	i (Pa s)	z (m)
5	3.48	115300	6010	160	28700	99
50	5	184000	7360	130	40300	96
95	6.5	246800	11450	115	56600	93

[a] For Eq. (5), the correct combination of overpressure and impulse corresponding to Y has been obtained combining the PROBIT equation with the Flixborough's characteristic curve [1].

Table 4
Iso-damage values and curves for several levels and types of damages

Affected population R (%)	PROBIT Y	Eardrum rupture (Eq. (2))	Death head impact (Eq. (4))	Death body impact (Eq. (5))	Death lung haemorrhage (Eq. (7))
5	3.48	$P_s = 38200$	$i = \frac{3.34\times10^8}{P_s - 2.03\times10^3}$	$i = \frac{6.97\times10^8}{P_s - 3.96\times10^3}$	$i = \frac{1.3\times10^3\times P_{ef}}{P_{ef} - 3.22\times10^5}$
50	5.00	$P_s = 103600$	$i = \frac{4\times10^8}{P_s - 2.43\times10^3}$	$i = \frac{1.3\times10^9}{P_s - 7.38\times10^3}$	$i = \frac{1.7\times10^3\times P_{ef}}{P_{ef} - 4.2\times10^5}$
95	6.5	$P_s = 277300$	$i = \frac{4.77\times10^8}{P_s - 2.90\times10^3}$	$i = \frac{2.4\times10^9}{P_s - 1.36\times10^4}$	$i = \frac{2.2\times10^3\times P_{ef}}{P_{ef} - 5.45\times10^5}$

taken into account is Eq. (7), since P_{ef} is the effective pressure and depends on the position of the body (standing, lying, near a wall, etc) and is calculated from the equations given by [15]. For these reasons, Eq. (7) has been selected in this paper.

3. Methodology

Once the PROBIT equations have been selected, iso-damage curves are represented in the same diagram as VCE characteristic curves. This allows a direct relationship between expected degrees of damage and distance to explosion's centre to be established. This methodology can be applied to every VCE taking only explosion energy and charge strength as inputs. To perform this operation the following steps must be carried out:

1. Selected PROBIT equations are taken, in this case—Eqs. (2), (4), (5) and (7).
2. Target percentages of affected population are established (R). In this paper 5, 50 and 95% are used. For these percentages Y values of 3.48, 5.00 and 6.5 are calculated respectively, by means of Eq. (11).
3. When these Y values are substituted in the above PROBIT equations, the iso-damage values or curves are obtained, as shown in Table 4.

   As deduced from Table 4, for eardrum rupture a unique iso-damage value is obtained for each R value, determined by side-on overpressure, since this type of damage depends only on that parameter. For the rest of types of damage and for each R value iso-damage curves are characterized by overpressure-impulse relationships.
4. The iso-damage values and curves obtained in the previous step are represented in an overpressure–impulse diagram where the characteristic curve of the targeted VCE is overlaid. As an example, the Flixborough explosion (characterized by an explosion energy of 1.42×10^{12} J and a charge strength of 10, as indicated in ref. [1]) has been represented in Fig. 2. The main damages as a function of distance have been included in Table 5.
5. This methodology can be applied to a wide range of VCEs. To carry out this operation, a set of VCE characteristic curves (characterized by explosion energy and charge strength) can be represented together with the iso-damage curves (PROBIT equations corresponding to the selected percentages of affected population). In Figs. 3–5 the characteristic curves for VCEs with charge strength of 10 together with the main iso-damage curves have been represented.

Some general conclusions can be drawn. The first is that eardrum rupture is the type of damage that humans would suffer at greater distances from the explosion. It can also be noted that death due to skull fracture (head impact) would occur at greater distances than death due to whole body impact (since the head is more fragile than the body). It must be taken into account that these two types of damage would occur only if humans hit rigid objects when their body was displaced. Finally, lung damage would occur only close to the centre of the explosion. In this example, the most conservative situation is plotted, that is, when humans are situated in front of a surface on which the shock wave reflects.

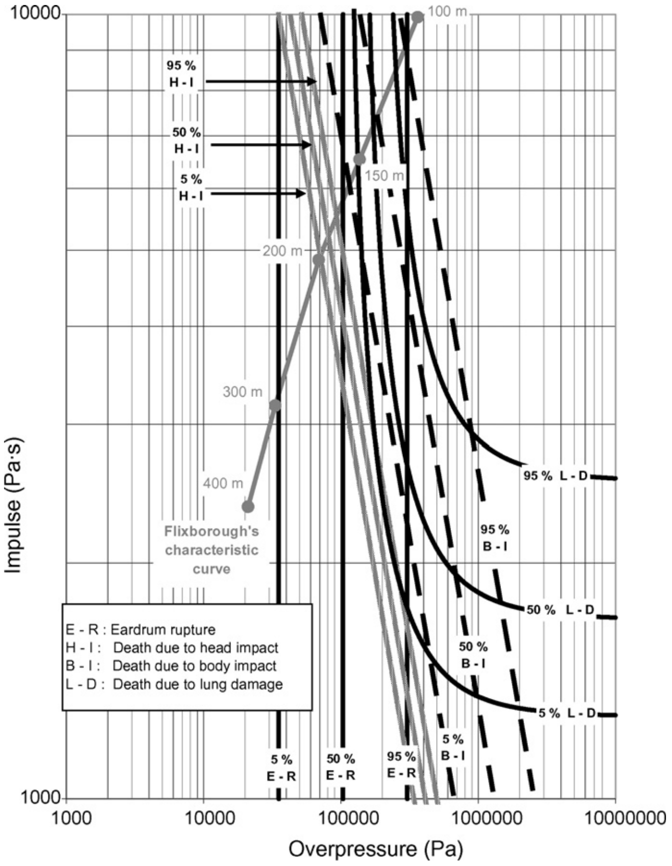

Fig. 2. Consequence analysis for humans outdoors from the Flixborough VCE (United Kingdom, 1974) with a Multi-Energy charge strength of 10 and releasing 1.4×10^{12} J of explosive energy [1].

Table 5
Consequence analysis for humans outdoors from the Flixborough vapour cloud explosion (United Kingdom, 1974) with a charge strength of 10 and releasing an explosive energy of 1.42×10^{12} J [1]

Distance from the explosion's centre (m)	Main damages on humans
100	95% eardrum rupture
	100% death due to skull fracture
	100% death due to body impact
	100% death due to lung haemorrhage
150	63% eardrum rupture
	100% death due to skull fracture
	12% death due to body impact
	4% death due to lung haemorrhage
200	24% eardrum rupture
	1% death due to skull fracture
	0% death due to body impact
	0% death due to lung haemorrhage
300	4% eardrum rupture
	0% death due to skull fracture
	0% death due to body impact
	0% death due to lung haemorrhage
400	1% eardrum rupture
	0% death due to skull fracture
	0% death due to body impact
	0% death due to lung haemorrhage

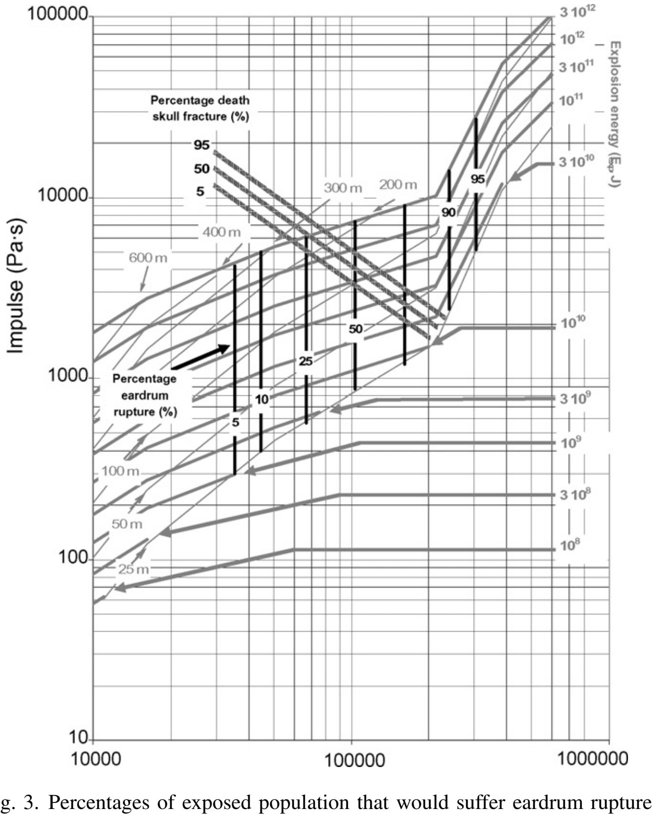

Fig. 3. Percentages of exposed population that would suffer eardrum rupture (black solid lines) or would die due to skull fracture (semi-dotted lines) as a function of distance (thin grey lines) and explosion energy (thick grey lines) for VCEs with a Multi-Energy charge strength of 10.

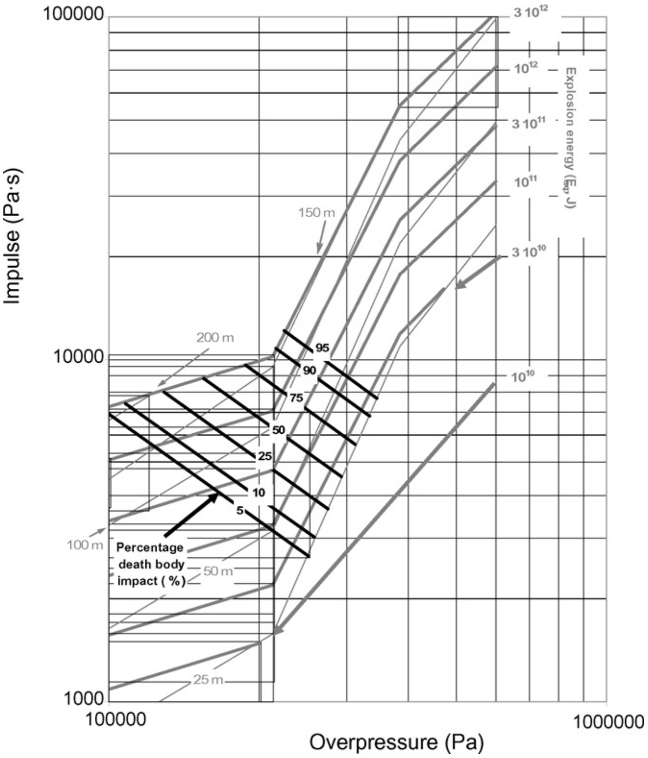

Fig. 4. Percentages of exposed population that would die due to whole body impact (black lines) as a function of distance (thin grey lines) and explosion energy (thick grey lines) for VCEs with a Multi-Energy charge strength of 10.

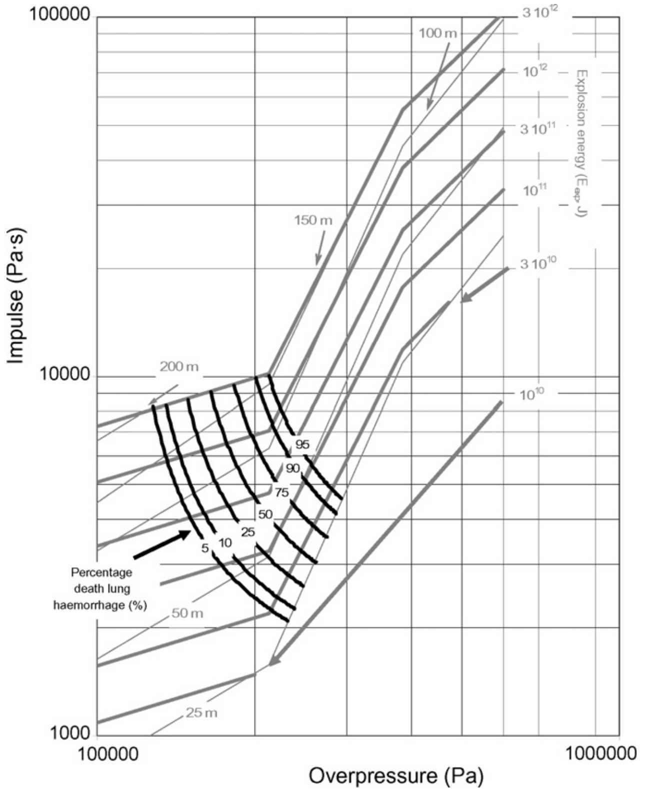

Fig. 5. Percentages of exposed population that would die due to lung haemorrhage (black lines) as a function of distance (thin grey lines) and explosion energy (thick grey lines) for VCEs with a Multi-Energy charge strength of 10.

Table 6
F' and Y values for each type of damage as a function of charge strength (N)

Type of damage	N	F'	Validity (interval F')	Y
Eardrum rupture	6	$z/E_{exp}{}^{1/3}$	$2.69 \times 10^{-3} < F' < 1.88 \times 10^{-2}$	$-3.36 - 1.69 \ln F'$
	7	$z/E_{exp}{}^{1/3}$	$1.29 \times 10^{-2} < F' < 2.15 \times 10^{-2}$	$-2.44 - 1.63 \ln F'$
		$z/E_{exp}{}^{1/3}$	$2.15 \times 10^{-2} < F' < 4.29 \times 10^{-2}$	$-5.47 - 2.41 \ln F'$
	8	$z/E_{exp}{}^{1/3}$	$6.63 \times 10^{-3} < F' < 2.58 \times 10^{-2}$	$-5.45 - 2.41 \ln F'$
	9	$z/E_{exp}{}^{1/3}$	$8.70 \times 10^{-3} < F' < 1.72 \times 10^{-2}$	$-8.02 - 3.09 \ln F'$
			$1.72 \times 10^{-2} \leq F' < 2.58 \times 10^{-2}$	$-5.45 - 2.41 \ln F'$
	10	$z/E_{exp}{}^{1/3}$	$9.58 \times 10^{-3} < F' < 2.15 \times 10^{-2}$	$-10.28 - 3.64 \ln F'$
			$2.15 \times 10^{-2} \leq F' < 2.58 \times 10^{-2}$	$-5.45 - 2.41 \ln F'$
Death due to skull fracture	7	$[(z/E_{exp}{}^{1/3})^{1.073} + (1.71 \times 10^{6}\ z^{1.563}/E_{exp}{}^{0.854})]$	$2.66 \times 10^{-1} < F' < 3.91 \times 10^{-1}$	$-4.61 - 8.49 \ln F'$
	8	$[(z/E_{exp}{}^{1/3})^{2.08} + (2.36 \times 10^{7}\ z^{3.11}/E_{exp}{}^{1.37})]$	$5.53 \times 10^{-3} < F' < 8.14 \times 10^{-3}$	$-37.48 - 8.49 \ln F'$
	9	$[(z/E_{exp}{}^{1/3})^{2.03} + (3.76 \times 10^{9}\ z^{4.29}/E_{exp}{}^{1.76})]$	$6.87 \times 10^{-3} < F' < 1.01 \times 10^{-2}$	$-35.65 - 8.49 \ln F'$ For $(z/E_{exp}{}^{1/3}) < 1.72 \times 10^{-2}$
		$[(z/E_{exp}{}^{1/3})^{1.58} + (2.53 \times 10^{7}\ z^{2.61}/E_{exp}{}^{1.20})]$	$3.71 \times 10^{-2} < F' < 5.46 \times 10^{-2}$	$-21.33 - 8.49 \ln F'$ For $(z/E_{exp}{}^{1/3}) \geq 1.72 \times 10^{-2}$
	10	$[(z/E_{exp}{}^{1/3})^{2.39} + (2.36 \times 10^{7}\ z^{3.42}/E_{exp}{}^{1.47})]$	$1.56 \times 10^{-3} < F' < 2.29 \times 10^{-3}$	$-48.24 - 8.49 \ln F'$
Death due to body impact	7	$[(z/E_{exp}{}^{1/3})^{1.073} + (1.83 \times 10^{6}\ z^{1.563}/E_{exp}{}^{0.854})]$	$5.43 \times 10^{-2} < F' < 2.08 \times 10^{-1}$	$-0.47 - 2.44 \ln F'$
	8	$[(z/E_{exp}{}^{1/3})^{2.08} + (2.53 \times 10^{7}\ z^{3.11}/E_{exp}{}^{1.37})]$	$1.13 \times 10^{-3} < F' < 4.33 \times 10^{-3}$	$-9.92 - 2.44 \ln F'$
	9	$[(z/E_{exp}{}^{1/3})^{2.03} + (4.03 \times 10^{9}\ z^{4.29}/E_{exp}{}^{1.76})]$	$1.40 \times 10^{-3} < F' < 5.38 \times 10^{-3}$	$-9.39 - 2.44 \ln F'$
	10	$[(z/E_{exp}{}^{1/3})^{2.39} + (1.50 \times 10^{20}\ z^{9.91}/E_{exp}{}^{3.68})]$ For $(z/E_{exp}{}^{1/3}) < 1.07 \times 10^{-2}$	$3.18 \times 10^{-4} < F' < 1.22 \times 10^{-3}$	$-13.01 - 2.44 \ln F'$
		$[(z/E_{exp}{}^{1/3})^{2.39} + (2.53 \times 10^{7}\ z^{3.42}/E_{exp}{}^{1.47})]$ For $(z/E_{exp}{}^{1/3}) \geq 1.07 \times 10^{-2}$		
Death due to lung haemorrhage	8	$[(z/E_{exp}{}^{1/3})^{2.57} + (3.43\ z^{1.03}/E_{exp}{}^{0.68})]$	$1.06 \times 10^{-5} < F' < 1.88 \times 10^{-5}$	$-59.10 - 5.74 \ln F'$
	9	$[(z/E_{exp}{}^{1/3})^{2.57} + (5.42 \times 10^{2}\ z^{2.26}/E_{exp}{}^{1.09})]$	$1.05 \times 10^{-5} < F' < 1.86 \times 10^{-5}$	$-59.15 - 5.74 \ln F'$
	10	$[(z/E_{exp}{}^{1/3})^{3.07} + (4.45 \times 10^{-1}\ z^{1.03}/E_{exp}{}^{0.67})]$	$1.38 \times 10^{-6} < F' < 2.44 \times 10^{-6}$	$-70.83 - 5.74 \ln F'$

For the values of N not indicated in the table, the maximum overpressure–impulse combination outside the flammable part of the cloud does not reach the minimum threshold that would produce each type of damage. F' dimensions are $(m^{1/3}\ s^{1/3}/kg^{1/3})^{x}$, being x the exponent of the first parentheses. For eardrum rupture, $x = 1$.

4. Numerical treatment

The diagrams of Figs. 3–5 are represented in a log–log scale, which can make difficult to perform an accurate reading. Furthermore, if this methodology is to be implemented in a computer model or a spreadsheet to allow a numerical estimation of the expected damage as a function of distance to the explosion's centre, it is necessary to take the iso-damage lines and the characteristic curves. The latter, obtained by [1], can be expressed as a relationship between overpressure or impulse and explosion energy and distance, as shown by Eqs. (12) and (13).

$$P_s = a \cdot [f(z, E_{exp})]^b \qquad (12)$$

$$i = c \cdot [f(z, E_{exp})]^d \qquad (13)$$

where a, b, c and d are fitting parameters used in ref. [1].

Combining Eqs. (12) and (13) for each charge strength with Eq. (1), equations relating PROBIT with energy and distance to the explosion's centre are obtained, as shown by Eq. (14).

$$Y = P + Q \cdot \ln[f(z, E_{exp})] = P + Q \cdot \ln F' \qquad (14)$$

where P and Q are fitting parameters. Finally, the combination of Eqs. (11) and (14) allows establishing relationships between percentage of affected population for each VCE (characterized by its explosion energy and charge strength) and distance to the explosion's centre. These equations are referred to here as fundamental equations. In Table 6 the expressions of F' and Y, for each *charge strength*, are indicated. The validity intervals for F' that should be taken into account to calculate Y are also indicated.

Finally, the methodological sequence to determine the level of damage caused by VCEs using the numerical equations indicated in Table 6 is the following:

1. Determination of charge strength (N) and explosion energy (E_{exp}). These parameters define the explosion itself.
2. Selection of a distance at which the degree of damage will be determined.
3. Calculation of F' by means of Table 6.
4. Verification of interval for F' indicated in Table 6.
5. Calculation of Y by means of Table 6. It must be noted that PROBIT (Y) is not expressed as a function of overpressure and impulse, but of distance and explosion energy.
6. Calculation of R (percentage of affected humans) by means of Eq. (11).

5. Conclusions

In an industrial explosion caused by ignition of a vapour cloud, characteristic overpressure–impulse–distance curves [1] can be used to determine the overpressure and impulse in only one step, allowing an overview of the evolution and the relationship of all the variables involved in vapour cloud explosions. Since damage caused by explosions depends chiefly on the overpressure and impulse, characteristic curves can be used to carry out consequence analysis. To perform this operation, PROBIT equations showing the relationship between magnitudes of the danger (overpressure and impulse) and percentage of the population affected have been selected and plotted in the same graph as the characteristic curves. As a result of this operation, human injuries can be directly assessed, avoiding calculations and allowing an overview of the evolution of the damage caused by VCEs. These figures also allow a comparison to be made of the damage as a function of the explosion energy and distance from the explosion.

When a more accurate result is needed, or when the methodology must be implemented by means of a computer program or a spreadsheet, fundamental equations in Table 6 can be used, which allow us to obtain the percentage of people affected by each type of injury simply as a function of distance and explosion energy for each charge strength.

In summary, using this new methodology, consequence analysis is simpler and faster.

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