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The quantitative assessment of domino effects caused by overpressure
Part I. Probit models

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Abstract

Accidents caused by domino effect are among the more severe that took place in the chemical and process industry. However, a well established and widely accepted methodology for the quantitative assessment of domino accidents contribution to industrial risk is still missing. Hence, available data on damage to process equipment caused by blast waves were revised in the framework of quantitative risk analysis, aiming at the quantitative assessment of domino effects caused by overpressure. Specific probit models were derived for several categories of process equipment and were compared to other literature approaches for the prediction of probability of damage of equipment loaded by overpressure. The results evidence the importance of using equipment-specific models for the probability of damage and equipment-specific damage threshold values, rather than general equipment correlation, which may lead to errors up to 500%.

Keywords: Domino effect; Blast wave; Probit analysis; Quantitative risk analysis; Explosion

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1. Introduction

Accidents caused by domino effect are among the more severe that took place in the chemical and process industry [1–5]. Therefore, the risk of domino effects is widely recognised in the legislation since the first "Seveso" European Community Directive (82/501/EEC) [6], which required the assessment of domino effects in the safety analysis of industrial sites falling under the obligations of the Directive. Furthermore, the "Seveso-II" Directive (96/82/EC) [7] extended these requirements to the assessment of domino effects not only within the site under consideration, but also to nearby plants.

Despite of the severe consequences of domino accidents, a well established and widely accepted methodology for the identification and the quantitative assessment of accidents caused by domino effects is still missing. Indeed, several qualitative criteria have been proposed in the literature to identify the possibility of domino events, mainly based on equipment vulnerability tables (e.g. see [1], and references cited therein), but only few quantitative approaches to the problem have been developed [8–11]. Moreover, in general these methods are based on oversimplified or not validated assumptions, in particular with respect to the models for the estimation of damage probability to process equipment.

On the other hand, several studies have pointed out that the availability of reliable models to assess damage probability to secondary targets (i.e. process equipment as tanks, reactors, etc.) is the key point for the quantitative assessment of risk caused by domino effects [8,11,12].

Overpressure is an important cause of domino effect. In a previous study based on the analysis of accident databases, Delvosalle [2] reported that 16.5% of domino accidents were caused by overpressure. In fact, 66 of the 105 "domino" accidents involving fixed installations were caused by an explosion involving nearby equipment, as reported in the MHIDAS database [13].

The present study focuses on the assessment and further development of probabilistic models for overpressure damage to process equipment in the framework of domino effect analysis. The modes and the characteristics of overpressure generation caused by accidental events in process plants were briefly revised, in order to identify the more likely causes of damage to process equipment. Available

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Nomenclature

B	constant
C_d	drag coefficient
D	tank diameter (m)
E_{exp}	total energy of explosion (MJ)
F	probability
F_d	probability of failure
H	height of the tank from the liquid level (void section) (m)
H_L	liquid level from ground (m)
I_s	positive impulse (kPa s)
k°	constant
k_1	probit coefficient
k_2	probit coefficient
P_{atm}	atmospheric pressure (kPa)
r	distance (m)
r_{th}	distance at which a threshold overpressure corresponding to 25% of probability of damage is reached (m)
R°	radius of unburned mixture (m)
R_f	flame path (m)
$\underline{R}_{ff}$	far-field distance, energy-scaled
r_{ff}	far-field distance (m)
t	time (s)
t_d	positive duration time (s)
V	dose (probit), for the analysis of blast damage $= \Delta P^\circ$ (Pa)
W	shell thickness (mm)
W_U	shell thickness in the upper section of the tank (mm)
W°	shell thickness in the lower section of the tank (mm)
Y	probit

Greek symbols

α	decay parameter
β	expansion factor
ΔP	static overpressure (kPa g)
ΔP_d	drag force (kPa g)
ΔP_F	buckling pressure (kPa g)
ΔP_q	dynamic pressure (kPa g)
ΔP_r	reflection overpressure (kPa g)
γ	specific heat ratio
μ	median of the Gaussian distribution
ρ	density (kg/m^3)
σ	variance of the Gaussian distribution

Subscript

b	burned mixture
u	unburned fuel mixture
$^\circ$	peak

data for equipment damage as a function of overpressure were revised and analysed for different categories of process equipment. Specific damage probability models were developed and compared to other literature approaches.

2. Overpressure damage to process equipment

2.1. Effective pressure for equipment damage

An explosion can be defined as the rapid release of energy into the atmosphere, thus generating a blast wave, which produces damages [14]. Actually, the definition extents its meaning to several different phenomena which can be categorised as condensed phase explosions (e.g. explosive charges), confined explosions (dust and gas explosion within equipment or buildings), boiling liquid expansion vapour explosions (BLEVE), runaway reaction explosion, physical explosion (e.g. the bursting of overfilled vessels), unconfined and partially confined vapour and gas explosion (VCE).

All these phenomena produce a blast wave whose interaction with objects is a very complex process involving reflection, refraction, flow separation. However, the observed damages are mainly related to the incident static overpressure (ΔP), to the positive impulse (I_s) and to drag forces on bodies (ΔP_d, the explosion wind), which in turn are strongly depending on body shape and orientation.

If most common industrial explosions are considered, i.e. excluding detonation of big amount of condensed explosives, and/or only far-field interactions between the point source of explosion and the target equipment are analysed, the drag forces are usually negligible. Indeed, ΔP_d is related to the dynamic pressure ΔP_q through a drag coefficient C_d. The value of ΔP_q grows with the static overpressure. When the peak static overpressure (ΔP°) is reached, the value of ΔP_q° is the maximum and can be calculated through the classical equation [15]:

$$\Delta P_q^\circ = \frac{\Delta P^{\circ 2}}{2\gamma P_{atm} + (\gamma - 1)\Delta P^\circ} \tag{1}$$

where γ is ratio of specific heats at constant pressure and volume, P_{atm} is the atmospheric pressure. It is easy to show that ΔP_q° is negligible for low ΔP° (for $\Delta P^\circ = 10$ kPa, $\Delta P_q^\circ = 0.035\Delta P^\circ$).

The shape (or the profile) of the pressure wave near the epicentre depends on the type of explosion involved. As the wave moves outwards, however, the influence of the nature of the explosion declines and the wave establishes a profile, which is common to all types of explosion. Eventually, the form of wave is similar and the time history of the overpressure can be evaluated using the modified Friedlander equation [16]:

$$\Delta P = \Delta P^\circ \left(1 - \frac{t}{t_d}\right) \exp\left(-\alpha \frac{t}{t_d}\right) \tag{2}$$

where t is the time, t_d the duration time and α is the decay parameter, which defines the shape of the decay curve in the positive phase. For overpressure lower than about 70 kPa the decay parameter is 1.0 [16].

The wall facing the explosion epicentre is stressed by the reflection overpressure (ΔP_r) of the wave front propagating along the surface according to the following equation [17]:

$$\Delta P_r = 2\,\Delta P + \frac{6\,\Delta P^2}{\Delta P + 7 P_{atm}} \tag{3}$$

According to this formula, the ratio $\Delta P_r/\Delta P$ lies within the limits $2 < \Delta P_r/\Delta P < 8$. The peak reflected overpressure is dependent on the peak overpressure and the peak dynamic overpressure through the equation [1]:

$$\Delta P_r^\circ = 2\,\Delta P^\circ + (\gamma + 1)\,\Delta P_q^\circ \tag{4}$$

The value of ΔP_r° approaches a value of twice the peak overpressure for weak shocks in which the peak dynamic pressure is negligible. Reflected overpressure should be considered if damage to equipment has to be predicted starting from pressure histories.

2.2. The “far-field” hypothesis

If domino effects within an industrial area are of concern, only the phenomena that can propagate damage at a significant distance from the source point of the explosion have to be considered. This point of view gives way to exclude from the present analysis several kinds of explosion whose consequences are catastrophic solely in the close surrounding of the source point (e.g. confined explosions, although accident propagation from confined explosions may take place due to missiles), restricting the interest essentially to vapour and gas cloud explosion (VCE), boiling liquid expanding vapour explosion (BLEVE), and explosion of great amounts of condensed explosives.

As distance from the boundary of explosion source increases, the influence of the nature of the explosion declines: thus, a “far-field” distance (r_{ff}) is defined as the effective threshold distance over which a freely propagating blast wave in the atmosphere is observed (i.e. not influenced by the actual shape of the energy source), and its total peak overpressure is low enough to neglect the effect of drag forces on body.

When BLEVE or, more in general, point-source explosion are considered, the air blast behaviour is ideal with the exception of the region in the immediate vicinity of the charge surface, since the source term interests a very limited area thus not influencing the blast propagation. The far-field hypothesis has a general validity for these events.

In the case of UVCEs, the flow field originated by the expansion of hot combustion products influences the source term. Thus, a different approach for the estimation of “far-field” threshold distance is needed. In view of the very large ignition energy required to initiate directly the detonation of a fuel–air mixture, detonation regime can be ruled out in practical conditions, whereas deflagration regime is more likely and sufficient to explain “experimental” observation of damage in vapour cloud explosion [18]. Hence, only deflagration will be considered in the following. For such relatively low Mach flames, the overpressure at the flame front represents the maximum overpressure in the system [19] and the maximum overpressure produced by the fuel–air explosion can be evaluated using the maximum effective flame velocity that is observed in the entire phenomenon. As a consequence, the blast wave produced by a vapour cloud explosion will propagate freely in the surrounding atmosphere, starting (conservatively) at the maximum flame front distance from the ignition point, supposed in the barycentre of the cloud. This length is often defined as the flame path, R_f. Thus, the value of R_f corresponds to the far-field threshold distance, r_{ff}. If an expanding hemispherical fuel air mixture is considered, mass conservation implies that the final flame radius R_f is given by:

$$R_f = R^\circ \left(\frac{\rho_u}{\rho_b}\right)^{1/3} = R^\circ \beta^{1/3} \tag{5}$$

where R° is the radius of the initial unburned mixture, and β is the expansion factor as given by the ratio of the density ρ of the unburned (u) over that of the burned (b) fuel air mixture. Of course, the “far field” threshold distance depends also on the total energy of explosion E_{exp}. Defining an energy-scaled “far-field” distance R_{ff}, as in the Sachs method used in the TNT approach, with respect to atmospheric pressure P_{atm} is then useful [20,21]:

$$R_{ff} = \frac{r_{ff}}{\sqrt[3]{E_{exp}/P_{atm}}} \tag{6}$$

The scaled distance varies with the combustible gas (or vapour) which forms the cloud and depends on the cloud shape. Examples of calculation of r_f and R_{ff} will be given in the following. The calculation of the actual far-field distance as well as the energy-scaled far-field distance represent an important preliminary check of the far-field assumption, that will be used in the following to develop damage probability models for process equipment.

2.3. Simplifying assumptions in the framework of quantitative risk analysis

Quantitative risk analysis (QRA) is usually performed on complex plants or even on extended industrial areas. Thus, a QRA generally requires simplifying assumptions both for the time evolution of the accidental phenomena and the consequence evaluation. An almost universal hypothesis used in QRA to model the consequences of explosions is to assume that all the accidental phenomena previously described produce blast waves which can be idealised and compared to the ideal blast wave produced by an equivalent charge of one or more solid “point” explosions (TNT, Baker–Strehlow and Multi-Energy methods) [21–23]. By these methods, peak overpressure ΔP° and impulse I° can be easily determined.

As previously observed, this simplification is only acceptable in the far field, whereas in the near field it often leads to the overestimation of pressure peaks. With respect to the assessment of damage to equipment, in a normal QRA context, the use of even simple “structural dynamics” codes and methodologies (SDOF) which analyse the response of structures for process equipment in industrial installations would not be acceptable. However, structural analysis for simple specimen can be still used as an “experimental” observation, in order to evaluate the destructive effectiveness of ideal blast waves on industrial equipment, in the far-field.

A further simplifying assumption consists of considering uniform blast load acting on the whole equipment, a conservative approach often used in the design criteria. This assumption is certainly acceptable when blast waves such as those produced by VCE impact either on small and medium scale equipment [24].

3. Available data on damage to equipment caused by overpressure

Several studies were found in the literature reporting data on damage to plant equipment caused by explosions. Most of the authors simply relate the peak static overpressure to the damage, unless structural analysis is considered.

Many studies report threshold values for damage to generic plant equipment, ranging from 7 to 70 kPa [8,11,25,26]. A summary of literature data collected is reported in Table 1. Among the other authors, here it is worth noting that Clancey [33] considers two kinds of damage: the displacement of equipment and the mechanical failure of the container. The threshold values are 20 and 27 kPa, respectively. On the contrary, Glasstone [17] proposes a maximum threshold value for the failure of connection of 7 kPa, hence lower than the value reported by Clancey [33]. This pressure value refers to the failure of tubes following the displacement of equipment and does not specify between pressure vessels and atmospheric vessels. Wells [35] considers different vulnerability for pressure vessels and atmospheric vessels. The former offers higher resistance to the peak overpressure due to the lower difference of pressure between the blast wave and internal pressure and to major inertia to displacement, due to the thickness of the walls of pressure vessels. The threshold overpressures reported are, respectively, 39 kPa for atmospheric vessel and 136 kPa for pressure vessels. Gledhill and Lines [26] proposed a threshold of 7 kPa for the damage of atmospheric equipment and of 38 kPa for pressurised vessels.

Schneider [32] has proposed “limit states” for specific equipment such as a distillation column (or more generally vertical cylindrical shell structure or column type equipment), for either sharp blast wave (point source explosion) or for the typical pressure wave of VCE in the far field. Four states can be then defined:

- *operating condition*: pressure does not exceed the allowable stress value of the material under consideration;
- *first limit state*: only part of the equipment reach the failure yield point;
- *second limit state*: fracture of shell;
- *third limit state*: disintegration of the structure or total collapse.

For the second limit state, the dynamical analysis performed gave a threshold pressure of 17 kPa for a vapour cloud explosion and of 29 kPa for a point-source explosion.

A first conclusion that may be drawn from the above analysis is that wide discrepancies exist between the data reported in the literature for damage to equipment as a function of overpressure. This may be caused by at least two factors: (i) ambiguity in the definition of “damage”: not all the data sources define accurately what is meant for equipment damage, and several types of damage are reported without any distinction (displacement, overturning, buckling, collapse); (ii) differences in the resistance of equipment to pressure waves: even equipment of the same category may have a different resistance to a pressure blast, and full details on structural or geometrical characteristics of the target equipment are not always provided.

Building a reliable model for overpressure damage to equipment requires an accurate revision of the above data, based on univocal definition of damage, overpressure and equipment characteristics. This point will be further discussed in the followings.

4. Models proposed in the literature for accident propagation caused by overpressure

As stated above, in the normal framework of QRA, only simplified models for damage to equipment would be acceptable. However, few attempts were made in the literature to model the probability of equipment failure because of overpressure.

The more simple approach proposed for the quantitative assessment of damage to equipment caused by overpressure is based on threshold values or vulnerability tables. Several authors propose to consider zero the probability of damage to equipment (damage not possible) if the value of overpressure is below a given pressure, and to assume a probability value of one (damage is sure) if overpressure is above the threshold value [9,10,26,38–40]. This approach is very simple, but has important drawbacks: the discontinuity of the probability function at the threshold value causes a high sensitivity of the model and may lead to severe errors either on the safe side or not. Furthermore, no agreement exists on the threshold values that range from 7 to 70 kPa.

Bagster and Pitblado [8] proposed an alternative approach, defining a damage probability function based on the distance

Table 1
Data reported in the literature for damage to process equipment caused by peak static overpressure (ΔP°)

ΔP° (kPa)	Damage	Reference
1.72	Minor damage, cooling tower	[27]
5.17	Minor damage, cone roof tank (100% filled)	[27]
5.17	Minor damage, cone roof tank (50% filled)	[27]
6.10	1% structural damage of equipment	[28]
7.00	Failure of connection	[17]
9.90	Failure of equipment	[25]
10.00	Failure of atmospheric equipment	[29]
10.00	5% damage of process plant	[30]
10.00	50% damage of atmospheric tank	[30]
14.00	Minor damage of cooling tower	[31]
14.00	Minor damage of atmospheric tank	[31]
17.00	Minor damage, distillation tower and cylindrical steel vertical structure. Failure of part of the equipment	[32]
18.70	Minor damage, floating roof tank (50% filled)	[27]
18.70	Minor damage, reactor: cracking	[27]
18.70	Catastrophic failure, cone roof tank (50% filled)	[27]
20.00	Displacement of steel supports	[33]
20.00	Tubes deformation	[31]
20.00	Deformation of atmospheric tank	[31]
20.00	20% damage, process plant	[30]
20.00	100% damage, Atmospheric Tank	[30]
20.40	50% structural damage of equipment	[28]
22.10	Minor damage, pipe supports	[27]
22.11	Catastrophic failure, cooling tower	[27]
24.00	20% of structural damage of steel floating roof petroleum tank	[34]
25.00	Atmospheric tank destruction	[31]
25.30	Minor damage, reactor chemical	[27]
27.00	Failure of steel vessel	[33]
29.00	Distillation tower and cylindrical steel vertical structure	[32]
30.00	Failure of pressure vessel	[29]
34.00	99% structural damage of equipment	[28]
35.00	80% damage of process plant	[30]
35.00	40% damage, Heavy machinery	[30]
35.50	Structural damage of equipment	[8]
35.71	Minor damage, fractionation column	[27]
37.42	Catastrophic failure, pipe supports	[27]
38.00	Deformation of non-pressure equipment	[31]
39.00	Structural damage to pressure vessel	[35]
39.12	Minor damage, pressure vessel horizontal	[27]
42.00	Tubes failure	[31]
42.00	Pressure vessel deformation	[31]
42.51	Minor damage, floating roof tank (100% filled)	[27]
42.51	Catastrophic failure, cone roof tank (100% filled)	[27]
42.52	Minor damage, extraction column	[27]
45.92	Catastrophic failure, fractionation column	[27]
47.00	Failure of non-pressure equipment	[27]
49.32	Minor damage, heat exchanger	[27]
52.72	Minor damage, tank sphere	[27]
53.00	Pressure vessel failure	[31]
53.00	Failure of spherical pressure vessel	[31]
55.00	20% of structural damage of spherical steel petroleum tank	[34]
59.52	Catastrophic failure, reactor chemical	[27]
59.52	Catastrophic failure, heat exchanger	[27]
61.22	Catastrophic failure, pressure vessel horizontal	[27]
69.00	Displacement and failure of heavy equipment	[27]
69.73	Catastrophic failure, extraction column	[27]
70.00	Structural damage of equipment	[36]
70.00	Deformation of steel structures	[31]
70.00	100% damage, heavy machinery, process plant	[30]
76.53	Catastrophic failure, reactor: cracking	[27]
81.63	Minor damage, pressure vessel vertical	[27]

Table 1 (*Continued*)

ΔP° (kPa)	Damage	Reference
81.63	Minor damage, pump	[27]
83.00	20% structural damage of vertical cylindrical steel pressure vessel	[34]
88.44	Catastrophic failure, pressure vessel vertical	[27]
95.30	99% structural damage of vertical, steel pressure vessel	[37]
97.00	99% damage of vertical cylindrical steel pressure vessel	[34]
108.84	Catastrophic failure, tank sphere	[27]
108.84	Catastrophic failure, pump	[27]
108.90	99% structural damage of spherical, pressure steel vessel	[37]
110.00	99% damage (destruction) of spherical steel petroleum tank	[34]
136.00	Structural damage, low pressure vessel	[35]
136.05	Catastrophic failure, floating roof tank (50% filled)	[27]
136.05	Catastrophic failure, floating roof tank (100% filled)	[27]
136.10	99% structural damage of floating roof tank	[37]
137.00	99% damage (destruction) of floating roof petroleum tank	[34]

from the center of the explosion:

$$F_{\rm d} = \left(1 - \frac{r}{r_{\rm th}}\right)^2 \qquad (7)$$

where $F_{\rm d}$ is the probability of failure, r the distance, and $r_{\rm th}$ the distance at which a threshold value of overpressure is reached. A main problem of Eq. (7) is that the probability of failure of secondary equipment is assumed to be always one (damage is sure) in the center of the explosion, and to decrease with the square of distance. This behaviour is completely unrealistic since the probability of damage may be lower than one even at the center of the explosion and the decrease of probability with the distance may show important deviations from the square law [1]. However, Eq. (7) may be modified in order to introduce at least a more realistic behaviour of the damage probability [41]:

$$F_{\rm d} = 1 \quad \text{if} \quad r < \tfrac{1}{2} r_{\rm th} \qquad (8)$$

$$F_{\rm d} = \left(\frac{3}{2} - \frac{r}{r_{\rm th}}\right)^2 \quad \text{if} \quad \frac{1}{2} r_{\rm th} \le r \le \frac{3}{2} r_{\rm th} \qquad (9)$$

$$F_{\rm d} = 0 \quad \text{if} \quad r > \frac{3}{2} r_{\rm th} \qquad (10)$$

where $r_{\rm th}$ is the distance from the center of the explosion at which the overpressure threshold value corresponding to 25% of the probability of damage is reached. Nevertheless, the model is still critically dependent on the estimation of a threshold value for the overpressure damage to equipment. As shown previously, wide uncertainties exist in the identification of these values.

DIN standards report simple equations for the definition of the maximum value of pressure that a tank can experience without a strong deformation (the "buckling" pressure $\Delta P_{\rm F}$) as a function of the geometry of the equipment. For typical oil tank this pressure can be computed by the following relationships [42,43]:

$$\Delta P_{\rm F} = 0.135 B \left(\frac{D}{H}\right)\left(10^4 \frac{W^{\circ}}{H_{\rm L}}\right)^{2.5}, \quad W_{\rm U} > 1.5 W^{\circ} \qquad (11)$$

$$\Delta P_{\rm F} = 0.135 \left(\frac{D}{H}\right)\left(10^4 \frac{W}{H_{\rm L}}\right)^{2.5}, \quad W_{\rm U} \le 1.5 W^{\circ} \qquad (12)$$

where W is the mean wall thickness between the shell thickness in the upper section of the tank $W_{\rm U}$ and the shell thickness of the lower section W°, D is the tank diameter, H is the height of the tank starting from the liquid level (the void section) and $H_{\rm L}$ is the liquid level height. The coefficient B varies with the ratio of shell thickness in the upper section of the tank to the lower shell thickness of the lower section, and in general has a value of about 2.0. Table 2 reports some examples of buckling pressures for atmospheric tanks of different volume. A filling level of 50% was considered; the geometrical characteristics of the tanks are shown in the same table.

The value of buckling pressure may be assumed as a maximum safe value for atmospheric tanks, above which a significant loss of containment should be expected. Although this approach to the estimation of "safe" values of overpressure might be applied also in the framework of "domino effect" analysis, it has two important drawbacks: (i) it is limited to a single type of equipment (vertical cylindrical

Table 2
Buckling pressure ($\Delta P_{\rm F}$) for cylindrical fixed roof tanks, 50% filled

Volume (m^3)	D (m)	W_1 (mm)	W_2 (mm)	W_3 (mm)	H (m)	$H_{\rm L}$ (m)	$\Delta P_{\rm F}$ (kPa)
500	7.6	5	5	5	5.45	5.45	4.80
750	10	5	5	5	4.05	4.05	18.57
1000	12	6	6	6	4.55	4.55	22.68
5200	24	7	9	11	5.45	5.45	66.71

Three sections with different wall thickness W along the tank height are considered.

atmospheric tanks); (ii) an estimation of the safety margins between buckling pressure and peak static overpressure corresponding to the effective loss of containment of the tank is not given. Actually, the overpressure values obtained for buckling seem extremely conservative, also in comparison with data in Table 1.

Eisenberg et al. [28] used a simplified model to assess the damage probability of process equipment caused by blast wave. The authors defined a probability function called "probit function" (Y) to relate equipment damage to the peak static overpressure ΔP°:

$$Y = k_1 + k_2 \ln(\Delta P^{\circ}) \tag{13}$$

where Y is the probit for equipment damage, ΔP° is expressed in Pa, k_1 and k_2 are the probit coefficients ($k_1 = -23.8$ and $k_2 = 2.92$ as reported by Eisenberg et al. [28]).

The cited "probit analysis" is a well known method to evaluate the dose-effect relation for human responses to toxic substances, thermal radiation and overpressure, but can be also considered a useful statistical method to evaluate damages of equipment subjected to pressure waves in the mainframe of quantitative risk analysis [1,5,44]. It derives from the cumulative expression for a normal Gaussian probability distribution function [45]:

$$F = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{Y-5} \mathrm{e}^{-u^2/2}\, \mathrm{d}u \tag{14}$$

where F is the probability ($0 \leq F \leq 1$), and the term u is:

$$u = \frac{V - \mu}{\sigma} \tag{15}$$

where V is the independent variable or the "dose", μ and σ are the median and the variance of the Gaussian distribution. In Eq. (14), Y is the probit unit:

$$Y = k^{\circ} + \ln(u) = k_1 + k_2 \ln V \tag{16}$$

In dose–response analyses, the constant k° is usually set to five; otherwise, Y is less than zero for $F < 0.5$ [46].

The model of Eisenberg [28] was based on "experimental" evaluation of equipment displacement with the subsequent deformation and breakage of connections, hence not considering the direct catastrophic failure of equipment.

The probit approach was followed also by Khan and Abbasi [36], who proposed a probit function similar to the equation of Eisenberg, but substituting the static overpressure with the total pressure (the sum of static and dynamic pressure). For the typical far field, low pressure blast wave produced by industrial explosion the dynamic pressure can be considered as negligible with respect to the static pressure. However, Khan and Abbasi give the same probit coefficients of Eisenberg et al. [28].

In the framework of the quantitative assessment of domino hazards due to overpressure, the probit approach is very attractive, due to its simplicity and to the limited additional effort which is needed to implement the probit function in existing QRA algorithm. Moreover, probit models are not critically dependent on the definition of damage threshold values and may be easily modified to take into account specific categories of process equipment, when sufficient data are available. Therefore, probit analysis was applied in the present study both to revise existing models and to develop further the probabilistic models for the damage to specific categories of process equipment.

5. Probit analysis of data for overpressure damage to equipment

The main issue in the construction of probit functions for damages caused by overpressure mainly consists of identifying the physical meaning of the independent variable (the "dose"), of the "effect" and of the consistency of the "representative sample" used to build the statistic function. Indeed, the use of statistical methods implies that analytical models are not able to reproduce the complex behaviour of phenomena, which in turn can be statistically predicted once a sufficiently large sample test is available. Thus, with specific reference to the blast waves characterised by a peak value of pressure, in the present analysis it was assumed that:

- far-field interactions between blast waves and equipment allows dynamic pressure to be neglected. Hence, the probit functions were be based on static peak overpressure, assumed as the independent variable;
- the maximum damage is likely observed when incident overpressure is perpendicular to the main section of equipment. Unless directionality of explosion can be accounted in the risk analysis, this is a "conservative" approximation;
- when similar equipment are considered, the similar damages (e.g. displacement of connected tube, buckling of shell, destruction of vessel, etc.) is observed at approximately the same value of peak static pressure, unless consistent differences in the design are present (mainly with respect to the design pressure).

The last assumption allows a significant reduction of the representative sample if specific classes of equipment are analysed separately (e.g. horizontal cylindrical steel atmospheric vessels at the same fill level).

In order to build a probit function, it is necessary to define "reference" damage as the "effect" and to correlate all the experimental or theoretical observations to a probability of occurrence of the specific damage. To this aim, in the mainframe of domino hazard analysis, the reference damage of the target equipment was considered as a secondary event resulting in a "dangerous loss of containment" whose consequences (radiation, overpressure, and toxic concentrations) are at least comparable with those of the primary accident.

With specific reference to explosions, the probability of damage should be the unity ($F_{\mathrm{d}} = 1$) when a relevant loss of containment is observed, e.g., when the external pressure overcomes the allowable stress value of the material under consideration, or if one of the following events takes place:

- the catastrophic failure (catastrophic damage, total collapse, disintegration, fracture) of equipment;
- the violent overturning or displacement of road, rail tank or heavy equipment;
- the structural damage to the main system of containment for atmospheric and pressurised vessels.

On the other side, the probability of loss of containment is minimum ($F_\mathrm{d} = 0.01$: “minor damage”) when the pressure wave is sufficiently intense to produce a “buckling” of the equipment.

Unless specified, values of probability between the two limits are difficult to define without any arbitrary choice. In the context of quantitative risk analysis as a comparative tool, two further hypotheses were introduced in the present study:

- a 10% failure probability was assumed to be correspondent to a partial failure, deformation, minor damage of the auxiliary equipment or to minor structural damage of atmospheric equipment;
- a 30% failure probability was assumed for the complete rupture of connections or for minor structural damage of pressurised equipment.

These assumptions were introduced since the failure of tubes can lead to the loss of containment if they contain hazardous substances, in particular in the case of pressurised equipment. In addition, the tearing of connections (e.g. welded or flanged to the shell) may cause a loss of containment from the main vessel.

Based on these considerations, the data reported in Table 1 were analysed in order to obtain failure probabilities of different “target” equipment as a function of overpressure (Tables 3–6). Data were divided in four categories: (a) atmospheric vessels, (b) pressurised vessels, (c) elongated vessels, and (d) small equipment. Equipment not belonging to these categories was not considered in the analysis whereas the data related to the piping failure were included in all categories.

The analysis of Tables 3–6 clearly shows that even dividing the equipment behaviour to overpressure by categories, the data are still rather dispersed or even contradictory. This is confirmed by the analysis of the corresponding probit values, also reported in the tables. Eventually, rather poor results are obtained if a direct correlation of damage data to overpressure is performed. Hence, in order to select the data that seem more reliable with respect to the present approach, the mean value and the mean square error of overpressure data corresponding to each probit value were calculated. Data whose differences with respect to the mean value exceeded the mean square error were discarded in the analysis. By this technique, reliable probit correlations were obtained, as shown in Table 7.

The correlation of failure probability with respect to overpressure is shown in Fig. 1. Fig. 2 shows a comparison of the probit values obtained for the different process equipment categories as a function of overpressure. As expected,

Table 3
Probability and probit values assigned to literature data for damage to atmospheric vessels caused by peak overpressure (ΔP°)

ΔP° (kPa)	Damage	Damage probability (%)	Probit
5.17	Minor damage, cone roof tank (100% filled)	1	2.71
5.17	Minor damage, cone roof tank (50% filled)	1	2.71
6.10	1% structural damage of equipment	1	2.71
7.00	Failure of connection	1	2.71
10.00	Failure of atmospheric equipment	1	2.71
14.00	Minor damage of atmospheric tank	1	2.71
18.70	Minor damage, floating roof tank (50% filled)	1	2.71
18.70	Catastrophic failure, cone roof tank (50% filled)	99	7.29
20.00	Displacement of steel supports	10	3.73
20.00	Tubes deformation	10	3.73
20.00	Deformation of atmospheric tank	10	3.73
20.40	50% structural damage of equipment	99	7.29
22.10	Minor damage, pipe supports	10	3.73
24.00	20% of structural damage of steel floating roof petroleum tank	99	7.29
25.00	Atmospheric tank destruction	99	7.29
27.00	Failure of steel vessel	99	7.29
34.00	99% structural damage of equipment	99	7.29
37.42	Catastrophic failure, pipe supports	30	4.48
42.00	Tubes failure	30	4.48
42.51	Catastrophic failure, cone roof tank (100% filled)	99	7.29
136.00	Structural damage, low pressure vessel	99	7.29
136.05	Catastrophic failure, floating roof tank (50% filled)	99	7.29
136.05	Catastrophic failure, floating roof tank (100% filled)	99	7.29
136.10	99% structural damage of floating roof tank	99	7.29
137.00	99% damage (total destruction) of floating roof petroleum tank	99	7.29

Table 4
Probability and probit values assigned to literature data for damage to pressure vessels caused by peak overpressure (ΔP°)

ΔP° (kPa)	Damage	Damage probability (%)	Probit
7.00	Failure of connection	1	2.71
20.00	Displacement of steel supports	10	3.73
20.00	Tubes deformation	10	3.73
22.10	Minor damage, pipe supports	10	3.73
30.00	Failure of pressure vessel	1	2.71
37.42	Catastrophic failure, pipe supports	30	4.48
39.00	Structural damage to pressure vessel	1	2.71
39.12	Minor damage, pressure vessel horizontal	1	2.71
42.00	Tubes failure	30	4.48
42.00	Pressure vessel deformation	30	4.48
52.72	Minor damage, tank sphere	1	2.71
53.00	Pressure vessel failure	30	4.48
53.00	Failure of spherical pressure vessel	30	4.48
55.00	20% of structural damage of steel spherical steel petroleum tank	99	7.29
61.22	Catastrophic failure, pressure vessel, horizontal	99	7.29
81.63	Minor damage, pressure vessel vertical	1	2.71
83.00	20% structural damage of vertical cylindrical steel pressure vessel	99	7.29
88.44	Catastrophic failure, pressure vessel vertical	99	7.29
95.30	99% structural damage of vertical, steel pressure vessel	99	7.29
97.00	99% damage of vertical cylindrical steel pressure vessel	99	7.29
108.84	Catastrophic failure, tank sphere	99	7.29
108.90	99% structural damage of spherical, pressure steel vessel	99	7.29
110.00	99% damage (total destruction) of spherical steel petroleum tank	99	7.29

Table 5
Probability and probit values assigned to literature data for damage to elongated vessels caused by peak overpressure (ΔP°)

ΔP° (kPa)	Damage	Damage probability (%)	Probit
7.00	Failure of connection	1	2.71
17.00	Minor damage, distillation tower and cylindrical steel vertical structure. Failure of part of the equipment	1	2.71
20.00	Displacement of steel supports	10	3.73
20.00	Tubes deformation	10	3.73
22.10	Minor damage, pipe supports	10	3.73
29.00	Distillation tower and cylindrical steel vertical structure. Failure of part of the equipment. Near field.	10	3.73
35.71	Minor damage, fractionation column	1	2.71
37.42	Catastrophic failure, pipe supports	30	4.48
38.00	Deformation of non-pressure equipment	10	3.73
42.00	Tubes failure	30	4.48
42.52	Minor damage, extraction column	1	2.71
45.92	Catastrophic failure, fractionation column	99	7.29
47.00	Failure of non-pressure equipment	99	7.29
69.73	Catastrophic failure, extraction column	99	7.29

Table 6
Probability and probit values assigned to literature data for damage to small equipment caused by peak overpressure (ΔP°)

ΔP° (kPa)	Damage	Damage probability (%)	Probit
7.00	Failure of connection	1	2.71
20.00	Displacement of steel supports	10	3.73
20.00	Tubes deformation	10	3.73
22.10	Minor damage, pipe supports	10	3.73
25.30	Minor damage, reactor chemical	1	2.71
37.42	Catastrophic failure, pipe supports	30	4.48
42.00	Tubes failure	30	4.48
49.32	Minor damage, heat exchanger	1	2.71
59.52	Catastrophic failure, heat exchanger	99	7.29
59.52	Catastrophic failure, chemical reactor	99	7.29
76.53	Catastrophic failure, reactor: cracking	99	7.29
81.63	Minor damage, pump	1	2.71
108.84	Catastrophic failure, pump	99	7.29

Table 7
Probit coefficients for different equipment categories (dose: peak overpressure in Pa)

Equipment	k_1	k_2	Regression coefficient	Mean square error (%)
Atmospheric vessels	−18.96	2.44	0.573	55.9
Pressurised vessels	−42.44	4.33	0.852	52.5
Elongated equipment	−28.07	3.16	0.690	5.3
Small equipment	−17.79	2.18	0.776	42.8

pressurised vessels showed the lower damage probabilities with respect to overpressure. Moreover, higher overpressure values resulted to be necessary to damage elongated vessels (as distillation or absorption columns) than atmospheric storage vessels.

Table 7 reports the mean relative errors of the probit correlations. As well as from the analysis of the discordances of data in Tables 3–6, it is again clear that the probit functions calculated in the present study may only be used as a rough estimate of the actual damage probability of process equipment with respect to overpressure. More reliable “experimental” data would be needed to reduce the error in the probit correlations. As shown in the table, errors as high as 50% on probability values may be expected. However, much higher errors (up to 500%) are obtained using a single probit correlation. The use of the other quantitative approaches previously described may lead to probability functions even less reliable, as discussed in the followings.

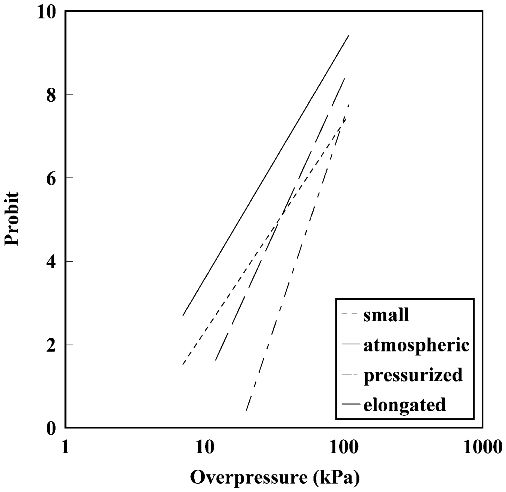

Fig. 2. Comparison of probit models obtained for the damage to process equipment caused by overpressure.

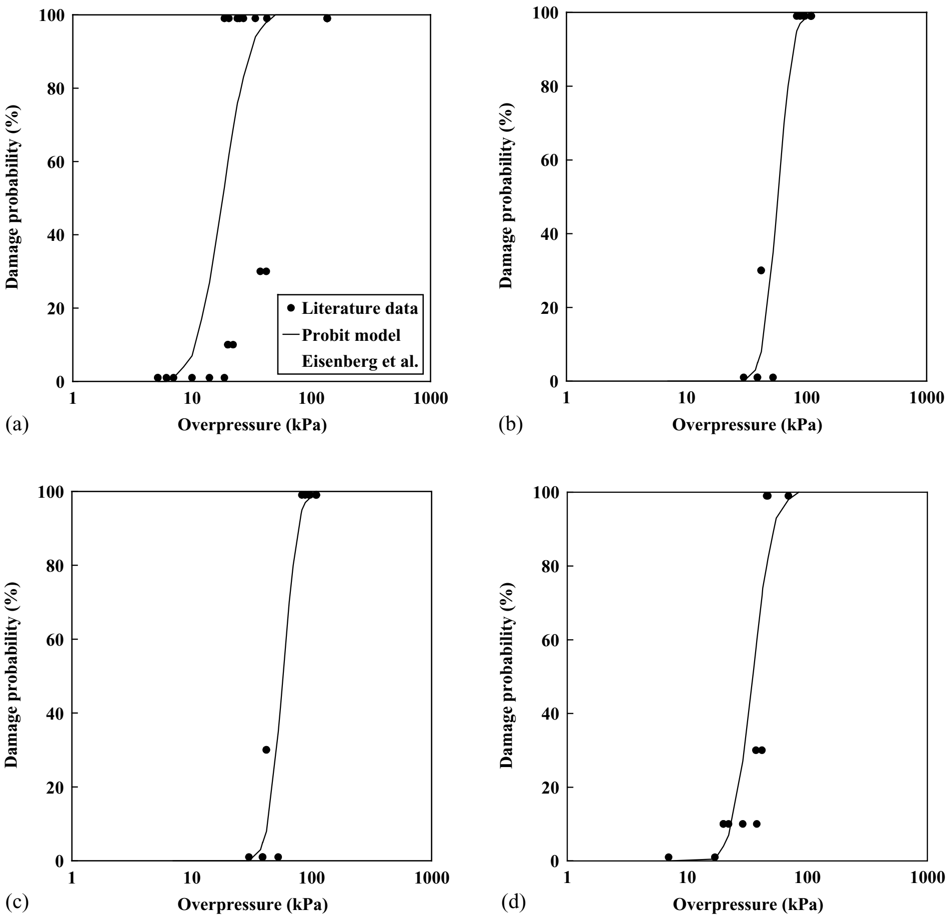

Fig. 1. Damage probability with respect to overpressure for: (a) atmospheric vessels; (b) pressurised vessels; (c) elongated vessels; (d) small equipment.

6. Assessment of equipment damage probability

6.1. Probit models

The probit models obtained from the analysis of available data for process equipment may be directly used for the assessment of equipment damage probability caused by blast waves. On the basis of models for blast wave propagation and of the previously developed probit models, figures for equipment damage probability as a function of distance scaled to the total energy from the center of the explosion may be easily obtained.

Fig. 3 reports a general comparison of the damage probabilities of pressurised and atmospheric equipment. In the figure, the blast wave propagation was evaluated by means of the Baker–Strehlow–Tang blast model [47]. The probit model obtained in the present study for atmospheric equipment gives results that are almost coincident with those obtained by the probit model reported by Eisenberg et al. [28]: less than 10% differences are present between the damage distances predicted by the two probit models. However, the distance at which the same damage probability is expected is three time higher for atmospheric equipment than for pressurised vessels. Differences of about a factor two are present between the different categories of atmospheric equipment, although very similar damage distances are found for small and elongated equipment.

Thus, it may be concluded that, at least if a TNT equivalency model is used, important differences are present in damage distances for different process equipment categories.

To extend the comparison and to better understand the importance of the differences of estimated damage distances, two specific cases were studied. Fig. 4 reports the overpressure as a function of distance calculated on the basis of the TNT model for the UVCE following the catastrophic rupture of an horizontal storage vessel containing propane (50 t) and a sphere containing butane (1000 t). For these two gases, the correspondent far-field distance calculated following Eq. (16), for spherical explosion at initial ambient pressure, is about 1.5. This value can be considered a critical value for the spherical explosion of all common hydrocarbons, provided that the combustion energy is 3.5 MJ/m^3 for any fuel air mixture and the expansion ratio is approximately 7.5. Fig. 5 shows the damage probabilities as a function of distance. Again, the figure confirms that very similar results are obtained from the probit model of Eisenberg et al. [28] and the model developed in the present study for atmospheric equipment. On the other hand, these examples clearly point out the differences among the estimated probabilities of failure for the different categories of equipment. As a matter of fact, distances at which a 20% damage probability is expected are up to 500 m lower for pressurised vessels with respect to atmospheric vessels.

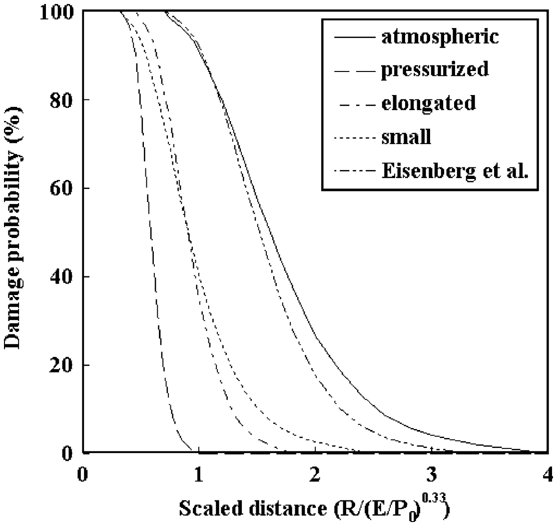

Fig. 3. Damage probability calculated using different probit models with respect to scaled distance from the explosion center.

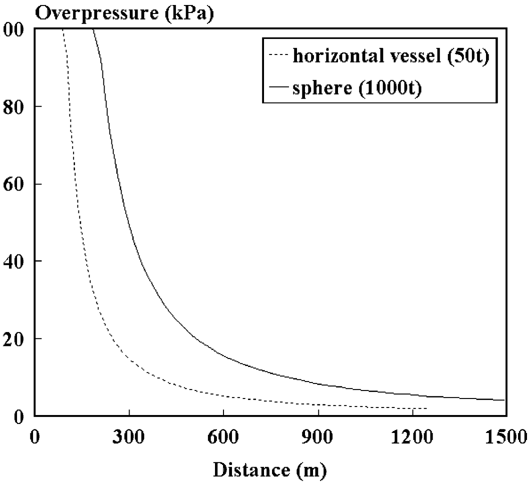

Fig. 4. Overpressure calculated for an UVCE following the catastrophic failure of a 50 t propane horizontal storage vessel and of a 1000 t butane sphere.

6.2. Damage thresholds

Fig. 6 reports the scaled distance from the explosion center at which the different threshold values reported in the literature for equipment damage are achieved. The Baker–Strehlow–Tang blast curve [47] was used again to calculate damage probabilities as a function of scaled distances. Differences up to a factor of four with respect to scaled distance can be observed in the same figure. Using overpressure curves as those in Fig. 4, differences up to 500 m are obtained between the distances at which the damage thresholds are reached, as shown in Fig. 7. Thus, it is clear that, if the analysis of a plant layout has to be performed in order to identify possible secondary targets of domino events caused by overpressure, wide differences are likely to result from the application of the different threshold values.

The comparison with probit models and with data reported in the literature for overpressure damage to process

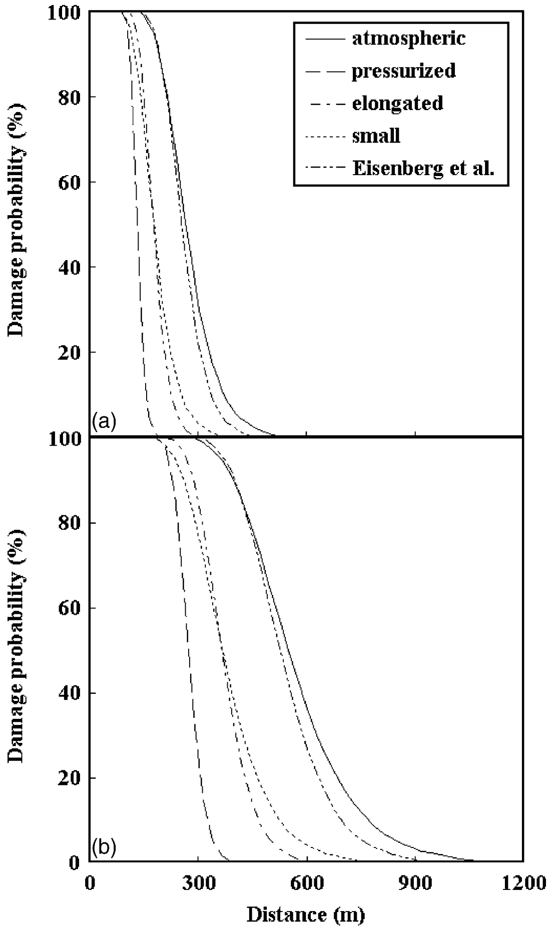

Fig. 5. Comparison of damage probabilities for damage to equipment following the UVCEs in Fig. 4: (a) 50 t propane vessel; (b) 1000 t butane sphere.

equipment clearly point out that the 70 kPa overpressure threshold proposed by some authors is not conservative, at least if atmospheric equipment is considered. On the contrary, the overpressure threshold value of 7 kPa proposed by Gledhill and Lines [26] seems the more conservative to be used if a preliminary identification of possible secondary targets of domino effect has to be performed.

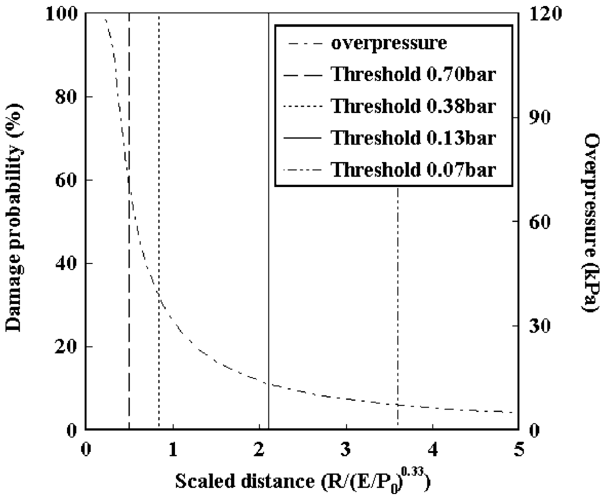

Fig. 6. Scaled distance from explosion center of overpressure threshold values, for damage to equipment.

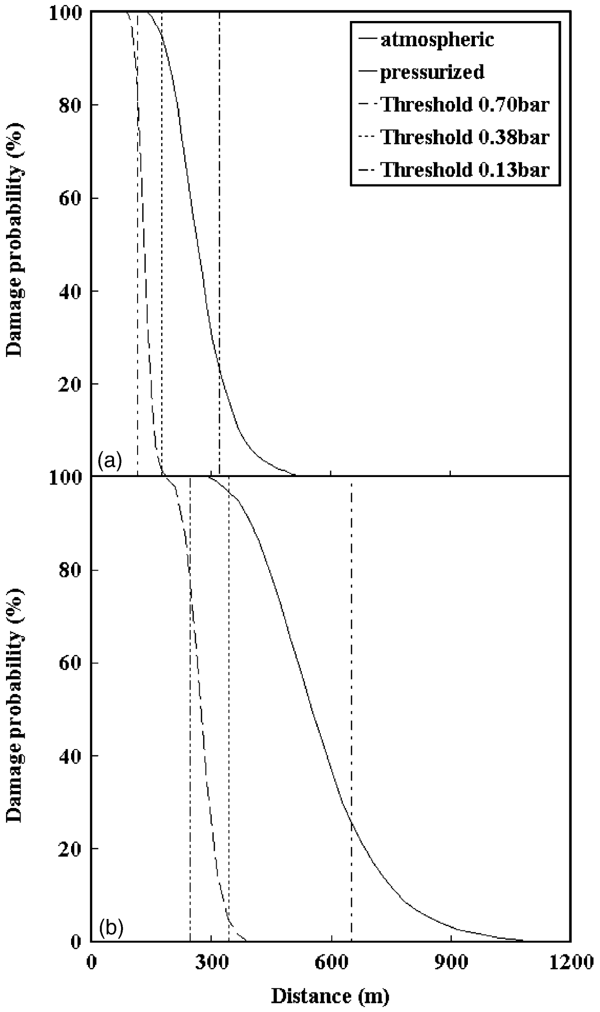

Fig. 7. Comparison of the position of threshold values for damage to equipment in the case of the UVCEs simulated in Fig. 4: (a) 50 t propane; (b) 1000 t butane.

However, the results obtained strongly suggest the use of different threshold values for the different equipment categories.

Data in Figs. 6 and 7 also show that the use of vulnerability tables based on a single threshold value for the quantitative assessment of domino effects may introduce important errors, either on the safe side or not.

6.3. Simplified models

A comparison of the damage probability values obtained from probit models and from the simplified approach proposed by Bagster and Pitblado [8] previously described is reported in Fig. 8. The comparison was possible only for specific cases, due to the features of the simplified models. The UVCE scenarios of Fig. 4 were used for the

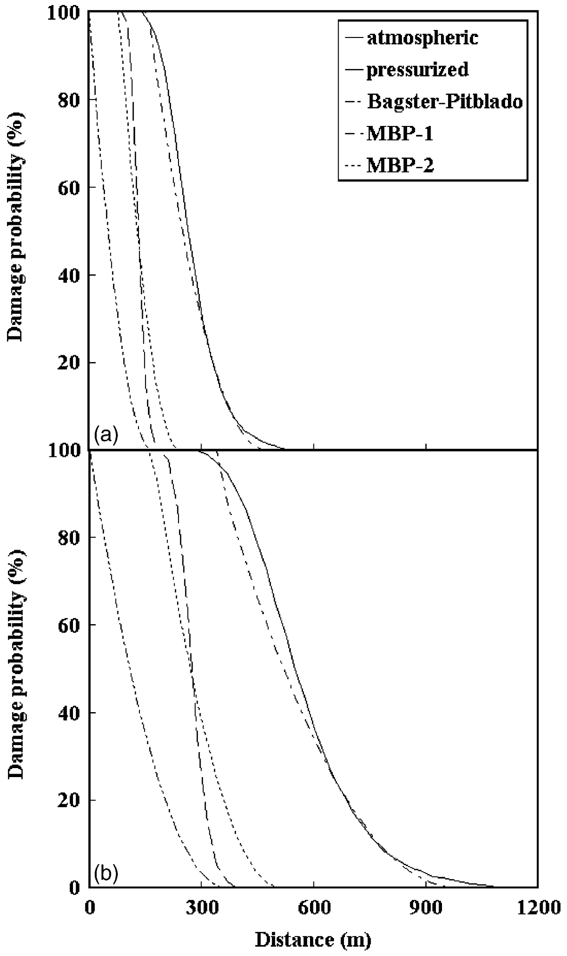

Fig. 8. Comparison of damage probabilities to process equipment calculated with different models for the UVCEs in Fig. 4 (MBP-1: modified Bagster–Pitblado model with an overpressure threshold value of 13 kPa; MBP-2: modified Bagster–Pitblado model with an overpressure threhsold value of 40 kPa). (a) 50 t propane and (b) 1000 t butane.

comparison. The results in Fig. 8 confirm that the original Bagster–Pitblado model is not reliable for the quantitative assessment of equipment damage, yielding results that seem not acceptable. On the other hand, the proposed modifications to the Bagster–Pitblado model result in damage probability curves that are very similar to those obtained from the probit approach and closer to literature data on equipment damage, as shown by a crosscheck with Tables 3–6. However, Fig. 8 confirms that an important drawback of this approach is the high sensitivity of the model to the threshold value adopted for the 25% failure probability.

7. Conclusions

Data reported in the literature for damage to equipment caused by pressure waves were revised. Although the quality of available data is scarce, a quantitative analysis was possible having considered separately the damage probability data for different process equipment categories.

The revision of models proposed for the assessment of damage to process equipment in the context of QRA suggested the use of probit models for the correlation of damage data. Of course, approaches that are more complex may be used for the calculation of damage to equipment related to an incident blast wave, but these would require a calculation effort that usually is not acceptable within a conventional QRA study.

Probit models for damage to equipment caused by blast waves were obtained and compared to available literature models. A good correspondence was found between the probit model obtained for atmospheric equipment and the model proposed by Eisenberg et al. [28]. On the other hand, relevant discordances were found with respect to other simplified approaches proposed. Moreover, important differences seem to be present between the damage probabilities and the damage threshold of different categories of process equipment. These results point out the importance of using equipment-specific models for the probability of damage and equipment-specific threshold values in the quantitative assessment of domino effects caused by overpressure.

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