The Effects of Explosive Blast on Structures and Personnel

Richard W. Prugh
Process Safety Engineering Inc., 207 Bancroft Building, Concord Plaza, Wilmington, DE 19810

Data concerning the effects of explosive blast on humans, structures, windows, etc. are available in standard texts. However, the "non-linear" relationships among the variables make it difficult to use the data in "what if" scenarios.

"Hyperbolic" equations which relate the energy of explosion (in terms of TNT equivalent), distance from the explosion, blast pressure, blast impulse and degree of injury or damage to structures are developed. These relationships may be shown as straight lines on "reciprocal-reciprocal" graph paper. Thus, correlation of blast-effects data is simplified, and fewer data points are required to characterize a damage-susceptible structure. Also, this type of graph aids in presenting the results of evaluations of potential damage which could result from accidental explosions, such as detonation of "condensed" explosives, pressure-vessel bursting, vapor-cloud explosions, and BLEVEs. Further, such graphs are useful in evaluating plant layouts and siting.

A. INTRODUCTION

The "Process Safety Management" standard of the Occupational Safety and Health Act (OSHA) [1] requires that the "consequences of failure of engineering and administrative controls" be addressed and requires "a qualitative evaluation of a range of the possible safety and health effects of failure of controls on employees in the workplace". Similarly, the "Risk Management Program Rule" of the U. S. Environmental Protection Agency [USEPA] requires an estimation of "the population within a circle with its center at the point of the release and a radius determined by the distance to the [1 psig] endpoint" [2]. Thus, the OSHA standard requires an assessment of the consequences of release and ignition of a flammable substance (or initiation of an explosive substance), in terms of injury potential or possible damage to occupied structures, and the USEPA standard requires that the explosion potential of a flammable-vapor release (or initiation of an explosive material) be determined and then converted to a 1-psig damage radius.

The purpose of this article is to present guidance concerning the effects of explosive blast on persons and structures, given the "TNT Equivalent" of the explosion. Obtaining a "TNT Equivalent" for various types of explosions, such as pressure-vessel burst, Boiling-Liquid Expanding-Vapor Explosion [BLEVE], unconfined or confined vapor-cloud explosion, deflagration involving self-reactive materials, and detonation of explosives, is outside the scope of this paper and is discussed in other references [3, 4].

There are two approaches to the evaluation of injury and loss potential. One is by direct correlations of the energy of an explosion (typically expressed in terms of TNT equivalent) and distance from the explosion. However, there are relatively few equations which correlate TNT equivalent to damage and injury.

The second approach to such evaluation is through the use of "Pressure/Impulse" diagrams [5, 6]. However, the author of "Loss Prevention in the Process Industries" notes that "The use of the P-I [Pressure-Impulse] diagram method [for explosion-hazards evaluation] is inhibited by the fact that there are few P-I diagrams available in the literature". Thus, one of the objectives of this paper is to present a compilation of the available pressure/impulse data. Another objective is to present an analysis of these data, and to present the pressure/impulse data in a form that would be useful in spreadsheet evaluations of explosion consequences. Included in this paper are several P-I diagrams for chemical-plant structures and off-site structures, based on observations resulting from accidental explosions and tests.

The data presented in this article are limited to reports where pressures and impulses were presented or could be deduced from information concerning the energy equivalent of the explosion and distances, together with reports of damage that could be quantified.

B. BLAST SOURCE STRENGTH

Most sources of explosive blast can be quantified in terms of TNT equivalent [3, 4]. For "condensed" or "point-source" detonating explosives, a TNT equivalent is obtained from the ratio of the heats of detonation [7]:

$$W_{TNT} = (H_{Det.}/1{,}400)\ W_{Explosive} \text{ pounds of TNT} \qquad (1)$$

Values of some heats of detonation appear in Table 1.

For "extended" and "non-detonating" sources (such as the bursting of pressure vessels, vapor cloud explosions, and

Table 1

Explosive	Heat of Detonation	Heat of Combustion
Composition B	1,515 cal./g.	2,775 cal./g.
Composition C-4	1,575 cal./g.	2,300 cal./g.
Nitrocellulose (14% N)	1,060 cal./g.	2,230 cal./g.
Nitroglycerine	1,600 cal./g.	1,610 cal./g.
TNT	1,400 cal./g.	3,600 cal./g.

Table. 2

"Free Air" Explosions		
$P_s=[(1,850/Z^{2.4})+(28/Z)]$	psig	(3)
$I_s=[43/Z^{0.9}]\ W^{1/3}$	psig-milliseconds	(4)
$P_r=[(3,200/Z^{2.5})+(55/Z)]$	psig	(5)
$I_r=[20/Z^{1.5}+(110/Z)]W^{1/3}$	psig-ms	(6)
"Surface" Explosions		
$P_s=[(2,600/Z^{2.6})+(32/Z)]$	psig	(7)
$Is=[65/Z^{0.91}]\ W^{1/3}$	psig-milliseconds	(8)
$Pr=[(1,600/Z^{2})+(60/Z)]$	psig	(9)
$Ir=[200/Z^{1.5}+(125/Z)]W^{1/3}$	psig-ms	(10)

BLEVEs), the TNT equivalent can be approximated as the ratio of the heats of combustion:

$$W_{TNT} = (H_{Comb.}/3,600)\ W_{Material} \quad \text{pounds of TNT} \qquad (2)$$

To account for the low pressure within the exploding material or container (as compared to the pressures of the order of 10,000 psig near the surface of detonating TNT), it may be necessary to use a "virtual distance" [8] so that the "far-field" effects of the explosion match those of an equivalent mass of TNT.

The effects of explosive strength and distance can then be quantified in terms of a "scaled distance" Z, according to U.S. Army Technical Manual TM5-1300 [9]:

$$Z = R / W^{1/3} \qquad \text{feet per pound}^{1/3}$$

where W is the equivalent weight of TNT (in pounds), and R is the distance from the center of the explosion (in feet).

For values of Z of 5 and greater, the values of "incident" (or "side-on") and "reflected" blast pressure P (in pounds per square inch, gauge [psig]) and impulse I (in psig-milliseconds) can be described adequately in the equations in Table 2.

In Table 2, the subscript s refers to "incident" or "side-on" pressures and impulses, and the subscript r refers to "reflected" pressures and impulses.

For the USEPA evaluations, the values of Z which correspond to "reflected" pressures of 1.0 psig - and the TNT Equivalents which could yield a pressure of 1.0 psig, for various distances - are described in Table 3.

As will be shown later, the only type of structural damage that is likely at a pressure of 1.0 psig is window-glass breakage, and the only type of injury that is likely to occur at 1.0 psig is laceration by broken window glass.

Bodily penetration of a 4-ounce (0.1 kilogram) glass fragment could occur if the fragment velocity was about 25 meters per second [10], or about 80 feet per second, or about 55 MPH. The "dynamic" pressure (caused by air displacement at a rate of 55 MPH) is given by:

$$\begin{aligned} P_d &= (1/2)\ \sigma\ v^2 / 144\ g_c\ ) = 8.1 \text{ x } 10^{-6}\ v^2 \\ &= 8.1 \text{ x } 10^{-6}\ 80^2 = 0.05 \text{ psig} \end{aligned} \qquad (15)$$

and by the Netherlands Organization of Applied Scientific Research [11] as:

$$\begin{aligned} P_d &= [2.5\ P_s^2\ ] / [7\ P_o + P_s\ ] = 0.05 \\ &= [2.5\ (1.5^2)\ ] / [7\ (14.7) + 1.5] \text{ psig} \end{aligned} \qquad (16)$$

That is, an "incident" or "side-on" pressure of about 1.5 psig would be required to cause serious injury from flying glass that was "loosely-retained" in a window frame. Thus, it appears that the USEPA blast-pressure "endpoint" of 1.0 psig is modestly conservative.

C. "TNT/DISTANCE/DAMAGE" CORRELATIONS

Perhaps the earliest attempt to quantitatively correlate blast damage, distance, and explosion energy involved a study of bomb damage during the Second World War [12, 13, 14,15]. The results of investigations into blast damage to

Table 3

Orientation: Reflected		Scenario			
		Elevated Explosion		Surface Explosion	
TNT Equivalent	$W^{1/3}$ (lbs.$^{1/3}$)	Z = 60 feet/lb.$^{1/3}$ (11)	Blast Impulse: $i_r/W^{1/3}$=1.7 (12)	Z = 75 feet/lb.$^{1/3}$ (13)	Blast Impulse: $i_r/W^{1/3}$=2.0 (14)
100 pounds	4.6	280 feet	7.8 psi-ms.	350 feet	9.2 psi-ms.
1,000 pounds	10.0	600 feet	17 psi-ms.	750 feet	20 psi-ms.
10,000 pounds	21.5	1,300 feet	36 psi-ms.	1,600 feet	45 psi-ms.

Table 4.

Damage Category	Damage Description	Values of A (ft./lb.$^{1/3}$)	
		Jarrett	Scilly
A	Uninhabitable and requiring demolition; demolished.	9.5	12.1
B	Uninhabitable and not repairable and requiring demolition; External brickwork 50% to 75% destroyed and structure rendered unsafe	14	17.9
Cb	Uninhabitable and not readily repairable; Partial or total collapse of roof, partial demolition of one or two external walls, and severe damage to load-bearing partitions requiring replacement	24	31.2
Ca	Uninhabitable, but readily repairable; Not exceeding minor structural damage to walls and roof, and severe window and door damage	70	53.7
D	Inhabitable, with inconveniences; Remaining inhabitable after repair: damage to ceilings and tiling; more than 10% of window panes broken	140	107
	Average "single-strength" (1/16") window-glass-breakage limit		2150

Table 5

Damage Percent	Damage Description	TNT Equiv. (pounds)	Distance (feet)	Incident Pressure (psig)	Reflected Pressure (psig)	Incident Impulse (psig-msec)	Reflected Impulse (psig-msec)	Value of A (ft./lb.$^{1/3}$) [Test No.]
80 % A	Uninhabitable and requiring demolition; demolished	16,000,000	3,500	5.0	12.5	1,750	4,000	13.8 [I-2]
		30,000,000	4,700	5.1	10.0	1,850	4,500	15.2 [II-2]
		30,000,000	4,700	5.1	10.0	1,850	4,500	15.2 [III-2]
40 % B	Uninhabitable and not repairable and requiring demolition	50,000,000	4,245	8.6	18.0	3,100*	7,500	11.5 [IV-2]
		30,000,000	5,500	4.0	8.0	1,630	3,500	17.7 [I-3]
		50,000,000	7,020	3.6	7.0	1,900*	4,000	19.1 [IV-1]
25 % Cb	Uninhabitable and not readily repairable	1,000,000	2,260	2.7	5.4	340	950	22.7 [I-9]
10 % Ca	Uninhabitable, but readily repairable	30,000,000	7,800	2.6	4.7	1,150	2,500	25.1 [I-4]
		200,000	1,660	1.6	3.8	161	420	28.4 [I-8]
		16,000,000	7,500	1.8	3.6	900	1,700	29.6 [I-1]
		30,000,000	10,500	1.7	3.0	840	1,900	33.9 [II-1]
		30,000,000	10,500	1.9	3.0	840	1,900	33.9 [III-1]
		1,000,000	4,000	1.1	2.4	185	500	40.0 [I-7]
		10,000	865	1.3	2.4	47	110	40.2 [I-5]
		10,000	865	1.2	2.4	44	110	40.2 [I-6]

* Apparent error in the original reference

Table 6.

Damage Category	Damage Description	Distance (feet)	Incident Press. (psig)	Reflected Pressure (psig)	Incident Impulse (psig-msec)	Reflected Impulse (psig-msec)	Values of A (ft./lb.$^{1/3}$) [Para. No.]
One story; Precast concrete wall and roof panels; earthquake resistant							
Ca	Usable, but requiring repairs	4,400	5.0	12.0	2,200	4,600	14.2 [4.38]
D	Usable, providing good protection, with inconveniences	9,200	1.7	3.5	1,100	2,100	30 [4.40]
One story; Reinforced masonry block walls and precast panel roof							
Ca	Usable, but requiring repairs	4,400	5.0	12.0	2,200	4,600	14.2 [4.42]
D	Usable, providing good protection, with inconveniences	9,200	1.7	3.5	1,100	2,100	30 [4.44]
One story; Steel frame with aluminum wall and roof panels							
Cb	Unusable; not readily repairable	6,000	3.1	6.9	1,600	3,400	19.4 [4.62]
Ca	Usable, but requiring repairs	12,000	1.2	2.5	800	1,600	38.5 [4.64]
One story; Self-framing corrugated steel wall and roof panels							
B	Unusable and not repairable and requiring demolition	6,000	3.1	6.7	1,600	3,400	19.4 [4.70]
Ca	Usable, but requiring repairs	12,000	1.2	2.5	800	1,600	38.5 [4.72]
One story; Self-framing flat steel wall and roof panels							
A	Unusable and requiring demolition; demolished	4,400	5.0	12.0	2,200	4,600	14.2 [4.128]
A	Unusable and requiring demolition; demolished	6,000	3.1	6.9	1,600	3,400	19.4 [4.66]
Cb	Unusable and not readily repairable	12,000	1.2	2.5	800	1,600	38.5 [4.67]

structures have been expressed in the form of the following equation:

$$R = A\,W^{1/3} / [\,1 + (7000/W)^2\,]^{1/6} \quad \text{feet} \qquad (17)$$

where $\underline{A}$ is a constant for a given "category" of damage (in feet per pound$^{1/3}$); and $\underline{W}$ is the explosion energy (expressed in pounds of TNT).

Definitions of the categories of damage to brick houses and values of $\underline{A}$ as determined by the original investigator and as later refined by others [12, 13] are shown in Table 4. Additional data concerning damage to brick and other types of houses [16, 17, and 18] are shown in Table 5.

For damage to industrial structures the values of $\underline{A}$ shown in Table 6 apply, where the pressures and impulses are the "incident" or "side-on" values (as contrasted with the "reflected" values), and the blast-energy equivalent was about 30,000,000 pounds of TNT ($W^{1/3}$ = 310) [18].

The apparent conflict between the values of $\underline{A}$ for Damage Category "D" for residential and industrial structures can be attributed to the assumption that industrial structures need not be "livable". The essential need for an industrial structure is to protect the equipment and contents in the building and to provide "reasonable" protection from the weather for employees that might need to work there.

The damage to industrial structures that resulted from an accidental explosion having a known TNT equivalent (about 20,000 pounds: $W^{1/3}$ = 27) is described in Table 7.

Additional data concerning structural damage [15] can be presented as shown in the Table 8. The values shown for "Z" (equal to the distance, in feet, divided by the cube root of the weight of an equivalent amount of TNT, in pounds of TNT) are for 22,000 pounds (10 metric tonnes) of TNT, but can be used for other TNT equivalents with a maximum "error" of about 20% [19, 20, 21].

D. "PRESSURE/IMPULSE/DAMAGE" CORRELATIONS

Damage to structures and injury to humans - as a result of exposure to explosions - are functions of blast overpressure (above atmospheric pressure) and blast impulse (the product of overpressure and (about one-half of) the overpressure duration) [22 through 30]. These responses to blast can be plotted on log-log graph paper in terms of overpressure and impulse. Typically, the forms of such curves are "near-hyperbolic"; that is, the curve asymptotically approaches a pressure value on the horizontal axis and asymptotically approaches an

Table 7

Damage Category	Damage Description	Distance (feet)	Incident Pres. (psig)	Reflected Pressure (psig)	Incident Impulse (psig-msec)	Reflected Impulse (psig-msec)	Values of A (ft./lb.$^{1/3}$) [Para. No.]
One story manufacturing buildings; Reinforced concrete							
D	Usable, providing good protection, with inconveniences	100	80	350	510	2,500	3.7
D	Usable, providing good protection, with inconveniences	150	33	115	430	1,400	5.6
One story process buildings; Steel frame with aluminum panels							
Cb	Unusable and not readily repairable	150	33	115	430	1,400	5.6
Cb	Unusable and not readily repairable	250	11	30	290	700	9.3
Cb	Unusable and not readily repairable	350	6.0	14	210	460	13.0
Cb	Unusable and not readily repairable	400	4.8	11	180	400	15.0
Cb	Unusable and not readily repairable	450	3.9	8.8	160	350	16.5
Ca	Usable, but requiring repairs	600	2.5	5.5	120	250	22.0
D	Usable, providing good protection, with inconveniences	1,300	0.9	1.9	60	120	48.0
One story; Unreinforced masonry block							
B	Unusable and not repairable and requiring demolition	500	3.3	7.4	150	310	18.0
Cb	Unusable and not readily repairable	700	2.0	4.4	110	230	26.0
Ca	Usable, but requiring repairs	800	1.7	3.6	90	190	30.0

Table 8

Element	Failure Mode	Value of "Z" (feet/lbs.$^{1/3}$)	Distance for 10,000 lbs/ TNT
Telephone Poles	Snapped	6.2	135 feet
Spherical Storage Tank	Overturns	7.7	165 feet
Brick-Faced Wood-Frame Houses	Cat. "A" Damage	9.0	190 feet
Railroad Box Cars	Derailed	9.0	190 feet
Extraction Column	Toppled	9.0	190 feet
8-inch-thick Brick Walls	Shattered	11.5	250 feet
Distillation Column	Toppled	12	260 feet
Piping Supports	Failure	13	280 feet
Brick-Faced Wood-Frame Houses	Cat. "B" Damage	14	300 feet
Large Storage Tanks	Ruptured	18	390 feet
Un-Reinforced Block Walls	Shattered	22.5	480 feet
Brick-Faced Wood-Frame Houses	Cat. "Cb" Damage	23	500 feet
Corrugated Siding	Shattered	32	700 feet
Brick-Faced Wood-Frame Houses	Cat. "Ca" Damage	40	850 feet
USEPA "Pressure Endpoint"	["Incident"]	45	970 feet
"Residential" Doors	Blown-in	52	1,100 feet
"Single-Strength" Windows	90% Breakage	70	1,500 feet
USEPA "Pressure Endpoint"	[if "Reflected"]	80	1,700 feet
Brick-Faced Wood-Frame Houses	Cat. "D" Damage	91	2,000 feet
"Single-Strength" Windows	50% Breakage	160	3,500 feet
Shrapnel and Missiles	Limit of Travel	300	6,500 feet
"Single-Strength" Windows	5% Breakage	400	8,500 feet
"Safe Distance"	No Damage or Injury	650	14,000 feet

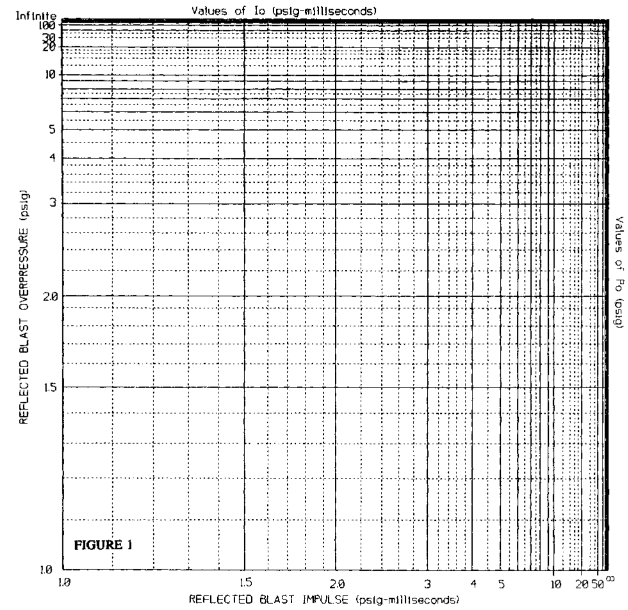


FIGURE 1.

Table 9

	Scenario	
	Elevated Explosion	Surface Explosion
Orientation	"Side-On"	"Side-On"
	"Perpendicular"	**"Perpendicular"**

impulse value on the vertical axis.

The relationships among TNT Equivalent, distance, blast pressure, and blast impulse have been determined experimentally and from investigations of accidental explosions [31, 32, 33]. There are four other variables involved, as displayed in Table 9.

Usually, the concern is for "perpendicular" exposure to blast waves, because "reflected" blast has at least twice the severity of the "side-on" or "incident" exposure [34], and for "Surface" explosions, since most flammable-vapor and potential-explosion sources are at or near ground level. This would be in contrast to "Free-Air" or "Elevated" explosions.

For explosions that might occur on a chemical plant, the blast pressures are relatively low. Also, many typical chemical-plant structures can be damaged by relatively low pressures. If it can be assumed that "hyperbolic" functions accurately describe blast-effects behavior, then the analysis of blast effects can be simplified and graphically displayed. Thus, a series of hyperbolic curves can be used to establish the extent or degree of damage to a particular class of structures or beings. Further, "hyperbolic" curves can be shown as straight lines on "reciprocal-reciprocal" graph paper.

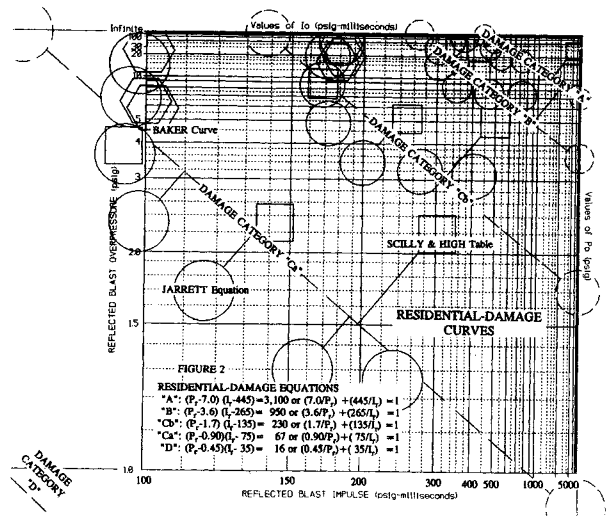


FIGURE 2.

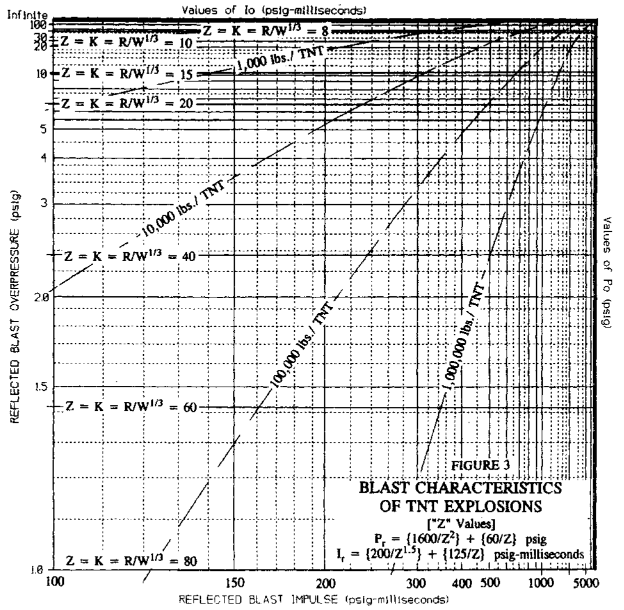


FIGURE 3.

E. "LINEARIZATION" OF BLAST-EFFECTS CURVES

Equations which describe hyperbolic curves are:

$$(Y - Y_0)(X - X_0) = K_1$$

or

$$(Y_0 / Y) + (X_0 / X) = K_2 \qquad (18)$$

These equations become identical if $K_1 = X_0Y_0$ and if $K_2 = 1$.

If blast pressure (reflected, or incident or side-on) $\underline{P}$ (in pounds per square inch [psig]) replaces $\underline{Y}$, and blast impulse (reflected, or incident or side-on) I (in psig-milliseconds) replaces $\underline{X}$, the preceding equations become:

$$(P - P_0)(I - I_0) = I_0P_0 \text{ psig}^2\text{-milliseconds} \qquad (19)$$

$$(P_0 / P) + (I_0 / I) = 1$$
$$(1/P) = -(I_0/P_0)(1/I) + (1/P_0) \text{ psig-1} \qquad (20)$$

Table 10

Fig.	Construction	Reflected-Pressure and Reflected-Impulse Equations for Damage Categories				
		D	Ca	Cb	B	A
		Usable; Providing Good protection; Inconveniences	Usable, but Requiring Repairs	Unusable; Not Readily Repairable	Unusable; Not Repairable; Requiring Demolition	Demolished Not Repairable
2	Residences	$(P_r-0.45)(I_r-35)=$ 16 psig^2-ms	$(P_r-0.9)(I_r-75)=$ 67 psig^2-ms	$(P_r-1.7)(I_r-135)=$ 230 psig^2-ms	$(P_r-3.6)(I_r-265)=$ 950 psig^2-ms	$(P_r-7)(I_r-445)=$ 3,100 psig^2-ms
4a	Reinforced Concrete Earthquake Resistant	$(P_r-6)(I_r-1500)=$ 9,000 psig^2-ms	[No Data]	[No Data]	$(P_r-15)(I_r-2000)=$ 30,000 psig^2-ms	$(P_r-20)(I_r-3000)=$ 60,000 psig^2-ms
4b	Reinforced Masonry Block	$(P_r-2.8)(I_r-600)=$ 1,700 psig^2-ms	$(P_r-5.5)(I_r-1200)=$ 6,500 psig2-ms	[No Data]	[No Data]	[No Data]
4c	Metal Panels on Steel Framework	$(P_r-1.05)(I_r-55)=$ 60 psig^2-ms	$(P_r-2.2)(I_r-115)=$ 250 psig^2-ms	$(P_r-5.5)(I_r-290)=$ 1,600 psig^2-ms	$(P_r-20)(I_r-1200)=$ 25,000 psig^2-ms	[No Data]
4d	Self-Framing Corrugated Steel Panels	[No Data]	$(P_r-2.2)(I_r-160)=$ 350 psig^2-ms	$(P_r-3.3)(I_r-250)=$ 850 psig^2-ms	$(P_r-5.5)(I_r-420)=$ 2,300 psig^2-ms	[No Data]
4e	Self-Framing Flat Steel Panels	[No Data]	[No Data]	$(P_r-2.2)(I_r-170)=$ 375 psig^2-ms	$(P_r-3.4)(I_r-260)=$ 880 psig^2-ms	$(P_r-5.8)(I_r-450)=$ 2,600 psig^2-ms
4f	Unreinforced Masonry Block	[No Data]	$(P_r-2.0)(I_r-85)=$ 170 psig^2-ms	$(P_r-2.4)(I_r-105)=$ 250 psig^2-ms	$(P_r-2.8)(I_r-120)=$ 340 psig^2-ms	[No Data]
5a	Tall Columns	[No Data]	[No Data]	$(P_r-4)(I_r-300)=$ 1,200 psig^2-ms	[No Data]	$(P_r-5)(I_r-450)=$ 2,000 psig^2-ms
5b	Window Panes (50% Broken)	[Not Applicable]	[Not Applicable]	[Not Applicable]	[No Data]	$(P_r-0.6)(I_r-1)=$ 0.6 psig^2-ms

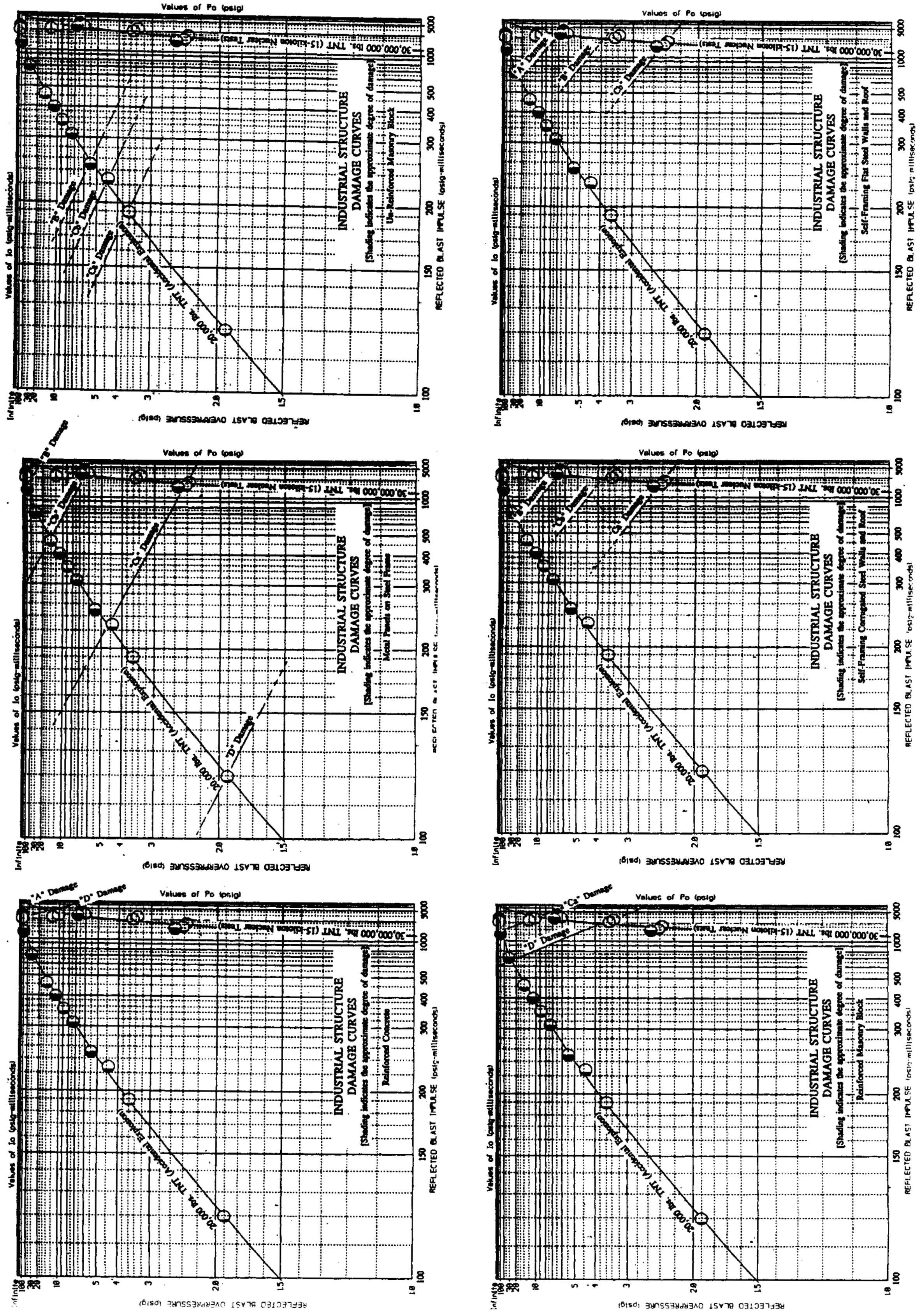
F. APPROXIMATE BLAST RESISTANCE OF STRUCTURES TO EXPLOSIVE BLAST

Table 10 presents equations which describe the straight-line relationships between reflected pressure, reflected impulse, and extent of damage for several types of construction which are typical in the chemical industry (with tall-column data obtained from reference [35]). The graphical plots from which the equations were obtained are presented as the Figures indicated.

A "Blast Characteristics" graph is presented as Figure 3, for use with Figures 1 and 2, and the TNT weights and distances can be used for Figures 4 and 5. Although interpolation might be justified - to evaluate structures for which "No Data" is shown in the above Table - methods for extrapolation beyond the observations would require techniques that are beyond the scope of this article.

Table 11

Fig.	Type of Injury	Reflected-Pressure and Reflected-Impulse Equations for Indicated Probabilities of Injury				
		1%	10%	50%	90%	99%
6	Fatal (Lungs)	$(P_r-27)(I_r-52)=$ 1,400 psig^2-ms	$(P_r-31)(I_r-61)=$ 1,900 psig^2-ms	$(P_r-38)(I_r-71)=$ 2,700 psig^2-ms	$(P_r-44)(I_r-91)=$ 4,000 psig^2-ms	$(P_r-53)(I_r-113)=$ 6,000 psig^2-ms
8	Eardrum Rupture	[No Data]	[No Data]	$(P_r-23)(I_r-45)=$ 1,000 psig^2-ms	[No Data]	[No Data]



INDUSTRIAL STRUCTURE DAMAGE CURVES
[Shading indicates the approximate degree of damage]
Un-Reinforced Masonry Block
Metal Panels on Steel Frame
Reinforced Concrete
Self-Framing Flat Steel Walls and Roof
Self-Framing Corrugated Steel Walls and Roof
Reinforced Masonry Block
Values of Po (psig)
Values of Io (psig-milliseconds)
REFLECTED BLAST IMPULSE (psig-milliseconds)
REFLECTED BLAST OVERPRESSURE (psig)
30,000,000 lbs. TNT (15-kiloton Nuclear Tests)
20,000 lbs. TNT (Accidental Explosion)
"A" Damage
"B" Damage
"C" Damage
"D" Damage
"Cs" Damage
Infinite
100
100
150
200
300
400
500
1000
5000
1.5
2.0
3
4
5
10
20
30

FIGURE 4.

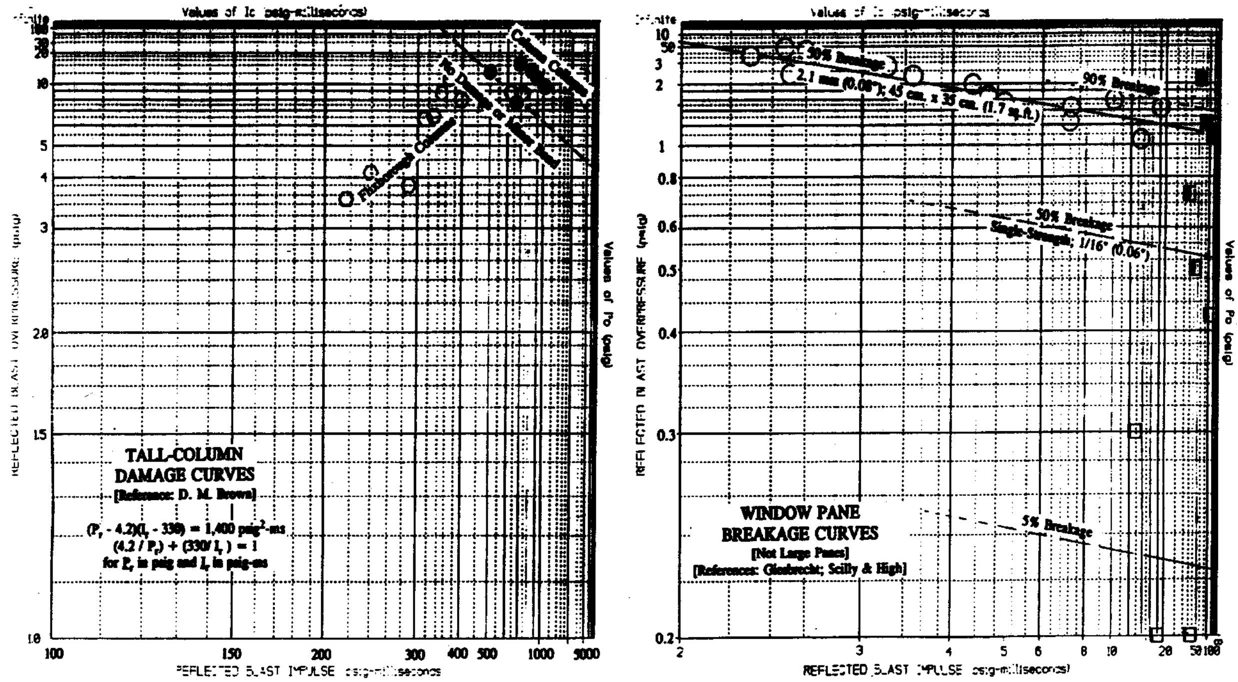


FIGURE 5.

G. HUMAN-INJURY RESISTANCE TO EXPLOSIVE BLAST

Table 11 presents equations which describe the straight-line relationships between reflected pressure, reflected impulse, and probability of fatal injury or eardrum rupture. The graphical plots from which the equations were obtained are presented as the Figures indicated. A "Blast Characteristics" graph is presented as Figure 7, for use with Figure 6.

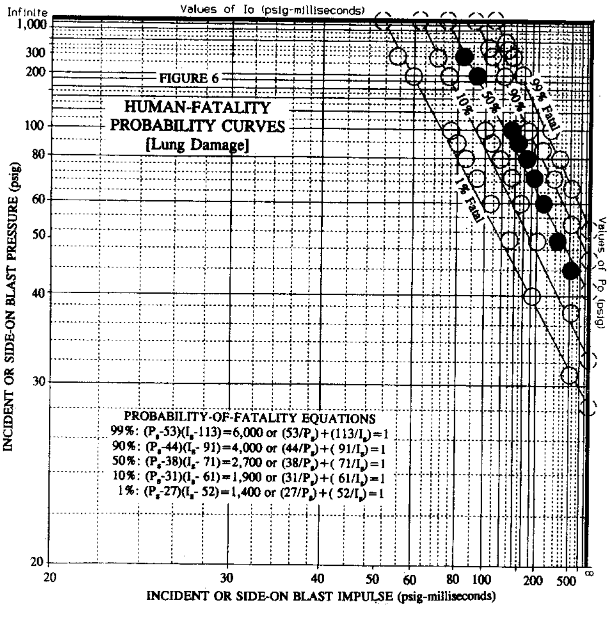
H. "PROBIT" RELATIONSHIPS

A "probit" equation is a method for relating the probability of an effect with the causative factor [36]. A general form of the probit equation is [37]:

$$Y = k_1 + k_2 V \tag{21}$$

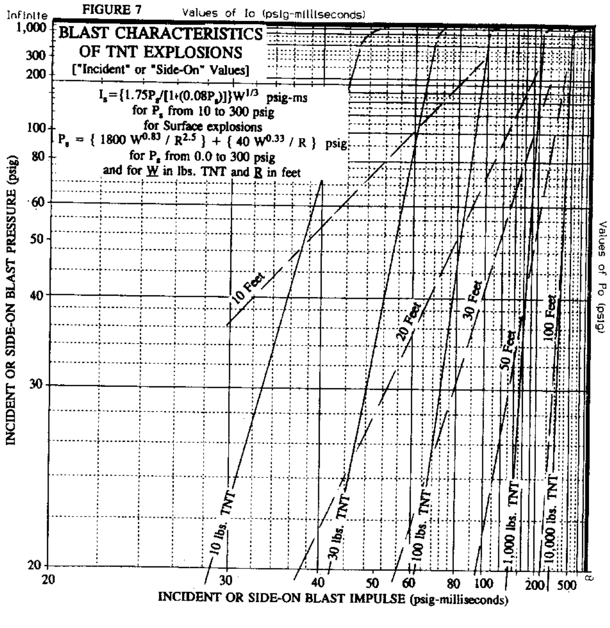
where $\underline{V}$ is the "intensity" of the causative factor; $\underline{k}_1$ is a constant (which has the value $\underline{5}$ if the logarithm of the causative factor fits a normal distribution, and $\underline{k}_2$ is a second constant, which enables correlation of the cause and effect.

Values of probability which correspond to probits are shown in Table 12.



PROBABILITY-OF-FATALITY EQUATIONS
99%: $(P_s-53)(I_s-113)=6{,}000$ or $(53/P_s)+(113/I_s)=1$
90%: $(P_s-44)(I_s-91)=4{,}000$ or $(44/P_s)+(91/I_s)=1$
50%: $(P_s-38)(I_s-71)=2{,}700$ or $(38/P_s)+(71/I_s)=1$
10%: $(P_s-31)(I_s-61)=1{,}900$ or $(31/P_s)+(61/I_s)=1$
1%: $(P_s-27)(I_s-52)=1{,}400$ or $(27/P_s)+(52/I_s)=1$

FIGURE 6. Human-fatality probability curves (lung damage).



$I_s = \{1.75P_s/[1+(0.08P_s)]\}W^{1/3}$ psig-ms
for P_s from 10 to 300 psig
for Surface explosions
$P_s = \{\ 1800\ W^{0.83} / R^{2.5}\ \} + \{\ 40\ W^{0.33} / R\ \}$ psig
for P_s from 0.0 to 300 psig
and for $\underline{W}$ in lbs. TNT and $\underline{R}$ in feet

FIGURE 7. Blast characteristics of TNT explosions

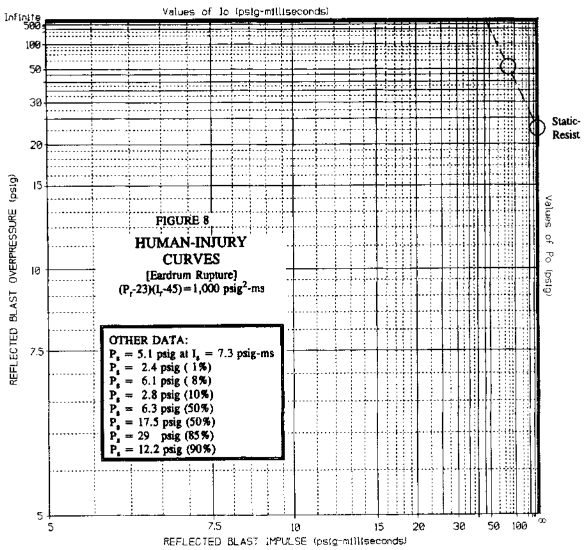


FIGURE 8. Human injury curves.

I. PROBIT EQUATIONS

To correlate the probability of blast injury or damage with "incident" blast pressures $\underline{P}_s$ (in psig) and "incident" impulses $\underline{I}_s$ (in psig-milliseconds), several probit equations have been developed:

Structural Damage [38]:

$$\begin{aligned} Y &= +5.00 - 2.92 \ln [(2.8/P_s)] \\ &= +2.0 - 2.92 \ln [(1/P_s)] \end{aligned} \tag{22}$$

Glass Breakage [38]:

$$\begin{aligned} Y &= +5.00 - 2.79 \ln [(0.57/P_s)] \\ &= +6.56 - 2.79 \ln [(1/P_s)] \end{aligned} \tag{23}$$

Fatal Injury from Lung Hemorrhage [39], for body weights near 155 pounds:

$$\begin{aligned} Y &= +5.00 - 6.91 \ln [(21/P_s)] \\ &= -16.0 - 6.91 \ln [(1/P_s)] \end{aligned} \tag{24}$$

$$\begin{aligned} Y &= +5.00 - 5.74 \ln [(62/P_s)+(250/I_s)] \\ &= -18.7 - 5.74 \ln [(1/P_s)+(4.0/I_s)] \end{aligned} \tag{25}$$

$$\begin{aligned} Y &= +5.00 - 6.6 \ln [(90/P_s)+(300/I_s)] \\ &= -24.8 - 6.6 \ln [(1/P_s)+(3.3/I_s)] \end{aligned} \tag{26}$$

$$\begin{aligned} Y &= +5.00 - 7.2 \ln [(40/P_s)+(80/I_s)] \\ &= -21.4 - 7.2 \ln [(1/P_s)+(2.0/I_s)] \end{aligned} \tag{27}$$

Fatal Injury from Impact [40]:

$$\begin{aligned} Y &= +5.00 - 4.82 \ln [(5840/I_s)] \\ &= -36.8 - 4.82 \ln [(1/I_s)] \end{aligned} \tag{28}$$

$$\begin{aligned} Y &= +5.00-2.44 \ln[(1.1/P_s)+(27{,}500/\{P_sI_s\})] \\ &= +4.83-2.44 \ln[(1/P_s)+(25{,}700/\{P_sI_s\})] \end{aligned} \tag{29}$$

Table 12

Probability	Y, Probit	Probability	Y, Probit
0.00003 %	0.01	3%	3.12
0.0001%	0.24	10%	3.72
0.001 %	0.73	15.9%	4.00
0.004 %	1.00	20%	4.16
0.01 %	1.28	30%	4.48
0.1 %	1.90	40%	4.75
1.4 %	2.00	50%	5.00
1.0 %	2.67	60%	5.25
2.3 %	3.00	Higher	$10.00\text{-}Y_{(100\text{-}\%)}$

Fatal Injury from Glass Fragments [41]:

$$\begin{aligned} Y &= +5.00 - 1.00 \ln [(12.6/P_s)] \\ &= +2.47 - 1.00 \ln [(1/P_s)] \end{aligned} \tag{30}$$

Eardrum Rupture [42, 43]:

$$\begin{aligned} Y &= +5.00 - 1.93 \ln [(6.3/P_s)] \\ &= +1.46 - 1.93 \ln [(1/P_s)] \end{aligned} \tag{31}$$

$$\begin{aligned} Y &= +5.00 - 0.87 \ln [(15/P_s)] \\ &= +0.87 - 1.52 \ln [(1/P_s)] \end{aligned} \tag{32}$$

Injury from Impact [44]:

$$\begin{aligned} Y &= +5.00 - 4.45 \ln [(2900/I_s)] \\ &= -30.5 - 4.45 \ln [(1/I_s)] \end{aligned} \tag{33}$$

Injury from Flying Fragments [45]:

$$\begin{aligned} Y &= +5.00 - 4.26 \ln [(275/I_s)] \\ &= -18.9 - 4.26 \ln [(1/I_s)] \end{aligned} \tag{34}$$

In the above equations which have a probit "intercept" value of +5.00, the 50%-damage values of blast pressure and/or blast impulse (or combinations) can be obtained by setting the value of the natural-logarithm function [in brackets] equal to 1.0 (in psig or psig-milliseconds, respectively).

As indicated by the above equations, considerable ranges of pressure and impulse values have been obtained by the various referenced investigators. For example, a factor of two in blast pressures near 10 psig could result in an order of magnitude difference in the probability of effect (or percentage of the exposed population that would be affected).

J. ADDENDUM

Several of the other aspects or degrees of injury, including vulnerability to injury if within a structure damaged by blast, are outside the scope of this presentation but are discussed in the literature [46, 47, 48].

A method for derivation of descriptive blast-effects equations is presented as Appendix B of the original version of this paper [49] and is available upon request to the author.

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