Methods for the determination of possible damage

to people and objects resulting from releases of hazardous materials

CPR 16E

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Voorburg, December 1989

The Director-General of Labour

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Contents

Introduction

Extend and Limitations of the "Green Book"

The so-called "Green Book" hereby presented contains a number of models, the extend and limitations of which are determined by: on one side, the knowledge about the effect-damage relations which is available and, on the other side, the budget limitations for the development of this book. In a number of cases, the knowledge available, from a strictly scientific point of view, was not sufficiently adequate to provide a back-up for the models presented in the book. An example of this is the use of data about toxicity, in the effect-damage models. On the basis of suggestions provided by the researches concerning the models to be applied, and pending more information, an agreement has been reached, within the CPR (Committee for the Prevention of Disasters), regarding the modelling which is presently applicable. In general, this present book about damage models must be considered as one corresponding to the time period of the investigations. Even when it was ready to be printed, some new results of investigations became available which, in turn, permitted to provide a better understanding of some of the subjects in question. This, for example, applies to models for "toxic combustion products" and to models for "damage caused by explosions".

The "Green Book" has been developed under a limited budget and, due to the needs of clarity and standardization, the cost of years of research was not justified. The budget limitations, coupled with time limitations, find, in the opinion of the CPR, their logical repercussions in a number of models presented. An example of this is the chapter "Population data".

In summary, it is the view of the CPR that this book must be regarded as a series of recommendations for the use of the damage models, and it must further be noted that for budgetary, practical and pragmatical reasons, it has sometimes recourse to generalizations over and above the specific knowledge of possibilities which is available. Nevertheless, the CPR feels that the book properly serves the purposes of clarity and standardization related to damage models, not withstanding the fact that valid reasons remain for further expansion and revision of the models in the future.

Voorburg, December 1989

The chairman of the committee for the Prevention of Disasters due to Dangerous Substances

Ir. E. Rombouts

VULNERABILITA'
dei soggetti esposti

__Analisi dei rischi di un impianto industriale__

- identificazione degli eventi incidentali (HAZARD)
-stima delle loro probabilità
-stima delle loro conseguenze
-stima dei danni alla poplazione e all'ambiente

CONSEGUENZE FISICHE

-mappe dell'intensità di irraggiamento termico da incendi
-mappe delle sovrapressioni da esplosioni
-mappe di concentrazioni di rilasci tossici

I danni all'uomo ed alle proprietà dipendono dell'entità delle conseguenze fisiche degli incidenti e dalla capacità di resistenza dei soggetti colpiti.

I MODELLI PREVISIONALI CHE PERMETTONO DI STIMARE I DANNI IN FUNZIONE DELLA AGGRESSIONE FISICA SONO NOTI COME

MODELLI DI VULNERABILITA'
(relazioni dose/danno)

Mappatura delle conseguenze fisiche → Modelli di vulnerabilità → Mappe di rischio (danni probabili)

Esplicitazione della vulnerabilità

-PROBIT
-DOSI DI SOGLIA

MODELLI DI VULNERABILITA' ALLE:

--- RADIAZIONI TERMICHE
--- ESPLOSIONI
--- SOSTANZE TOSSICHE

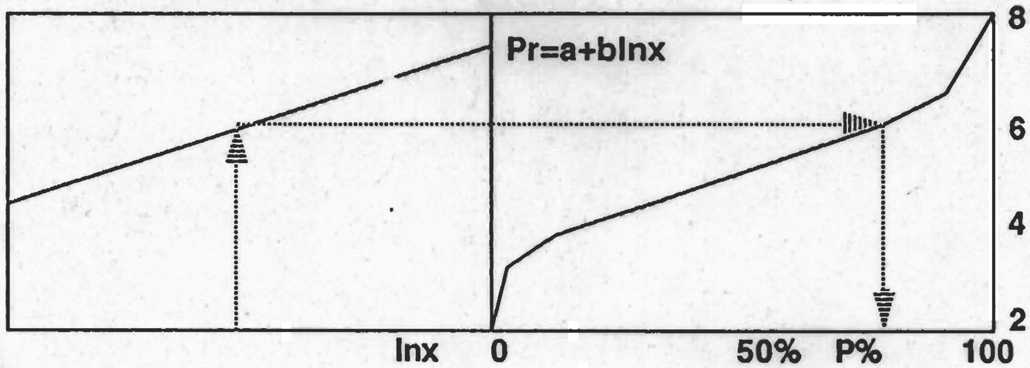
$$Pr = a + b \ln x$$

a,b = costanti

x = variabile che descrive l'entità dell'impatto fisico

Pr = misura della percentuale del danno sulle risorse (umane e/o materiali) esposte

Pr (*probability unit)* è una distribuzione gaussiana con valor medio 5 e varianza 1 (ad una percentuale del 50% corrisponde un valore della probit di 5)



9.6 PROBIT METHODS

In many of the situations considered in loss prevention it is necessary to relate the intensity of some phenomenon such as heat radiation from a fire, overpressure from an explosion or toxic gas concentration from a toxic gas release to the degree of injury or damage which can result from it.

The method increasingly used is probit analysis. An account of this method is given in *Probit Analysis* by Finney (1971). Its application to major hazards is described by Eisenberg *et al.* (1975).

The probit (probability unit) Y is related to the probability P by the equation

$$P = \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{Y-5} \exp\left(-\frac{u^2}{2}\right) du \qquad (9.6.1)$$

The probit is a random variable with a mean 5 and variance 1. The probability (range 0–1) is generally replaced in probit work by a percentage (range 0–100). The relationship between percentages and probits is shown in *Table 9.12* and in *Figure 9.12*.

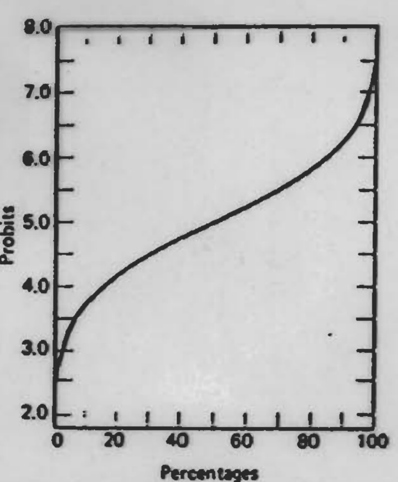


Figure 9.12 Relationship between percentages and probits (Finney, 1971) (*Courtesy of Cambridge University Press*)

A general form of the probit function is

$$Y = k_1 + k_2 \ln V \qquad (9.6.2)$$

where the probit Y is a measure of the percentage of the vulnerable resource which sustains injury or damage, and the variable V is a measure of the intensity of the causative factor which harms the vulnerable resource.

The logarithmic term in equation (9.6.2) arises from the fact that in most populations there are some

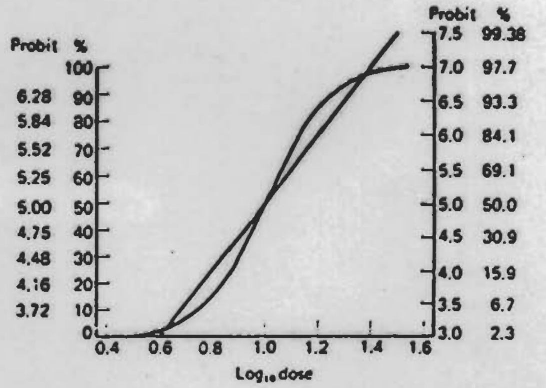


Figure 9.13 Effect of the probit transformation (Finney, 1971). The figure illustrates a typical experiment on the toxicity of an insecticide. The logarithm of the lethal dose fits a normal distribution. The figure shows the distribution function and the corresponding probit function (*Courtesy of Cambridge University Press*)

subjects who can tolerate a rather high level of the harmful causative factor. The distribution obtained is therefore skew. It is commonly found, however, that the logarithm of the causative factor fits a normal distribution. For a causative factor x which has such a distribution

$$Y = 5 + (\ln x - m)/\sigma \qquad (9.6.3)$$

where m and σ are the mean and standard deviation of the normal distribution, respectively. Equation (9.6.3) can be rewritten in the alternative form of equation (9.6.2).

The effect of the probit transformation is shown in *Figure 9.13*. The sigmoidal curve of the distribution function of the normal distribution is transformed into a straight line.

The variable V in equation (9.6.2) expresses the intensity of the causative factor. In some cases it is a single variable and in others it is a function of one or more variables. Thus Eisenberg *et al.* define V for eardrum rupture from an explosion

$$V = p^0 \qquad (9.6.4)$$

where p^0 is the peak overpressure. But for death from a toxic gas release

$$V = \int C^n \, dT \qquad (9.6.5a)$$

$$\simeq \sum C_i^n T_i \qquad (9.6.5b)$$

where C is the gas concentration, T the time of exposure, and n an index.

The constants k_1 and k_2 in equation (9.6.2) may be calculated from the data on the relationship between the intensity of the causative factor and the degree of

% Fatalities	0	1	2	3	4	5	6	7	8	9
0	-	2.67	2.95	3.12	3.25	3.36	3.45	3.52	3.59	3.66
10	3.72	3.77	3.82	3.87	3.92	3.96	4.01	4.05	4.08	4.12
20	4.16	4.19	4.23	4.26	4.29	4.33	4.26	4.39	4.42	4.45
30	4.48	4.50	4.53	4.56	4.59	4.61	4.64	4.67	4.69	4.72
40	4.75	4.77	4.80	4.82	4.85	4.87	4.90	4.92	4.95	4.97
50	5.00	5.03	5.05	5.08	5.10	5.13	5.15	5.18	5.20	5.23
60	5.25	5.28	5.31	5.33	5.36	5.39	5.41	5.44	5.47	5.50
70	5.52	5.55	5.58	5.61	5.64	5.67	5.71	5.74	5.77	5.81
80	5.84	5.88	5.92	5.95	5.99	6.04	6.08	6.13	6.18	6.23
90	6.28	6.34	6.41	6.48	6.55	6.64	6.75	6.88	7.05	7.33
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
99	7.33	7.37	7.41	7.46	7.51	7.58	7.58	7.65	7.88	8.09

Table 3.5 : *Transformation of Percentage Fatalities to Probits for Toxicity Calculations (Finney, 1971)*

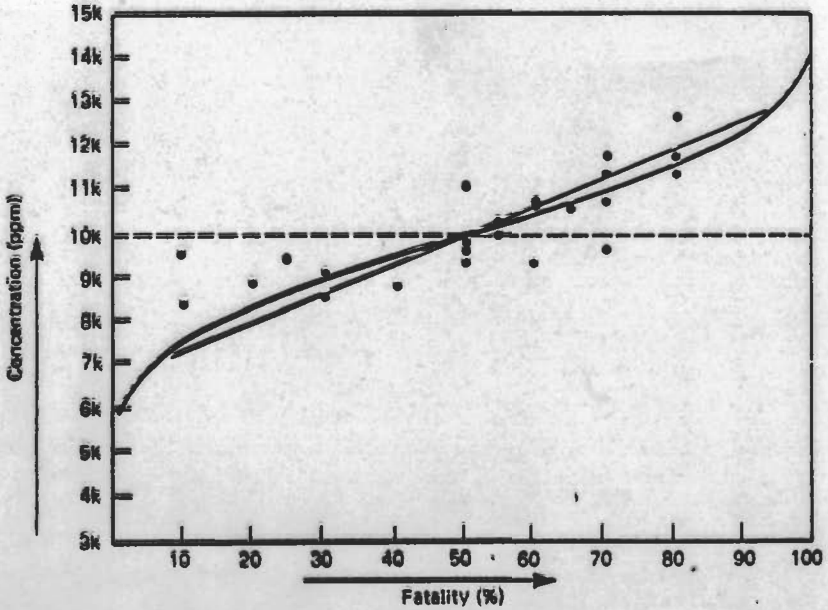


Figure 1.2 *Lethal toxicity of ammonia, linear plot*

A more detailed account of probit equations is given elsewhere.[9] Probit methods provide a very convenient way of extrapolating from data obtained over the range 20–80 per cent mortality, but it must be remembered that their use does not confer any greater precision than is inherent in the original data. Thus, there is obvious uncertainty in the slope of the line drawn through the experimental points obtained in the 20–80 per cent region and extrapolation of this uncertain line to levels of one per cent or less is open to large errors. Very large numbers of animals would have to be employed to obtain significant experimental data in the low percentage region.

Trevan also drew attention to the low level of confidence which may be given to the mean result if too few animals are used. It has been shown using Trevan's method that for small numbers of animals the confidence limits are wide even at the central 50 per cent mortality and that they become ever wider at the lower (and higher) mortalities. This is illustrated in Table 1.3, reproduced from a paper by Withers and Lees, giving ranges at the 95 per cent confidence level.[10]

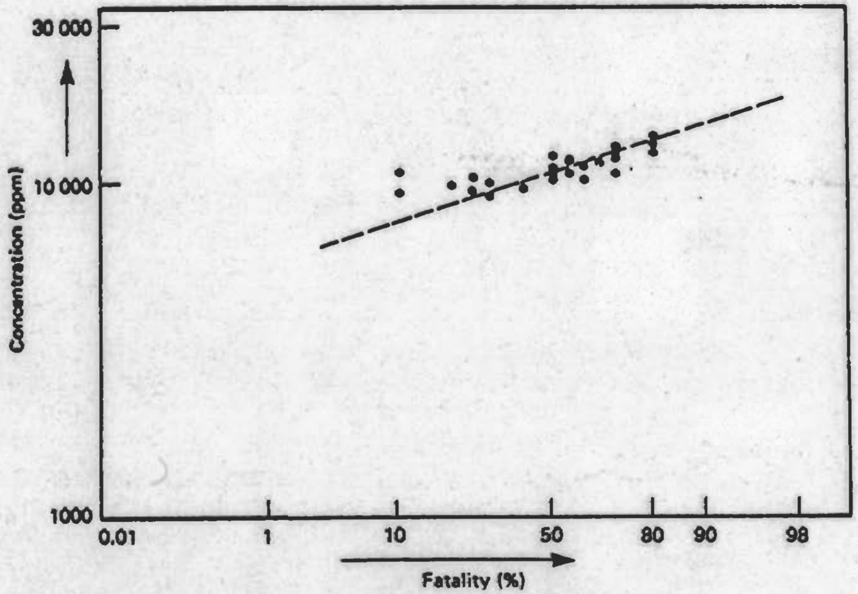


Figure 1.3 *Lethal toxicity of ammonia, log-probability plot*

Whilst it is clearly important that experiments be conducted with large numbers of animals, humanitarian and economic considerations usually provide a limiting constraint. As a result, even though considerable care is often taken to work within an

Table 1.3

Expected mortalities in groups of experimental animals, at 95 per cent confidence level

Mortality expected (%)	Number in set	Fatality range
50	10	2–8
	20	6–14
	30	10–20
	50	18–32
	100	40–60
25	30	3–12
	100	17–33
10	30	0–6
	100	4–16

VULNERABILITÀ

ESPLOSIONI

DANNI DA:

- DIRETTI DA IMPULSI DI PRESSIONE
- DA MISSILI E FRAMMENTI
- DA TRASLAZIONE E COLLISIONE DEL CORPO CON OSTACOLI

• MORTALITÀ DA IMPULSI DI PRESSIONE

$$Pr = -77.1 + 6.91 \ln P_p \qquad P_p = \text{sovrap. } [N/m^2]$$

(RICAVATA DA VULNERABILITÀ DELLO APPARATO POLMONARE)

ROTTURA DEL TIMPANO

PROBABILITÀ	SOVRAPRESSIONE
1 %	16500
10 %	19300
50 %	43500
90 %	84000

• FERITE DA MISSILI E FRAMMENTI

$$Pr = -27.1 + 4.26 \ln J \qquad (J = \text{impulso } [N\,s/m^2]$$

Table 8.1
Lovelace field experiments

Species		Average weight (kg)	Average pressure (psi)	Average time (milliseconds)	Mortality killed/tested
Sheep	1	52.5	164	3.18	31/65
	2	54.0	52	211	14/34
	3	52.6	1 307	0.30	7/22
Goats	1	22.7	111	3.81	7/15
	2	23.2	60.9	17.0	8/15
	3	21.7	55.8	38.7	16/28
	4	20.5	51.5	400	13/30
	5	24.7	295	1.2	6/12
Rabbits	1	1.9	78.9	1.12	32/49
	2	1.9	44	2.79	25/50
	3	3.7	25.7	354	17/32

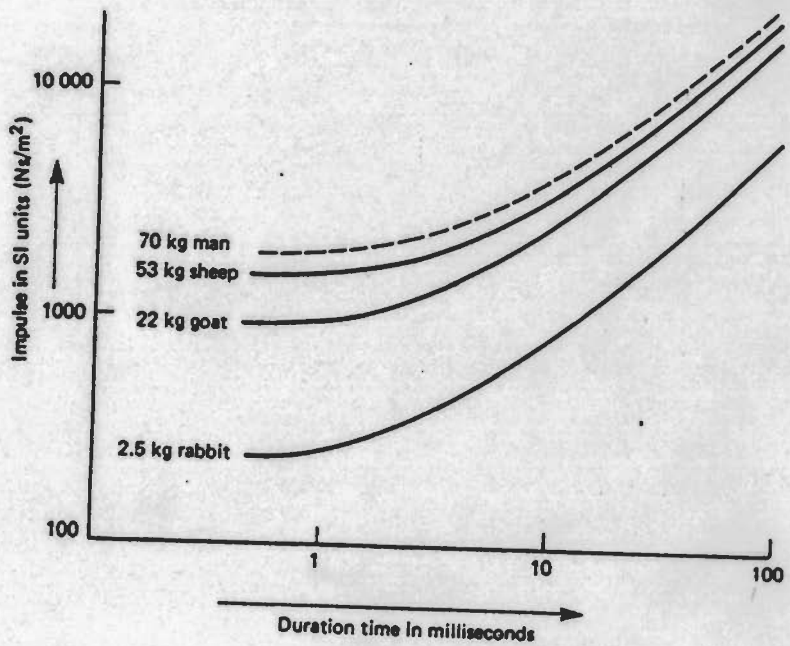


Figure 8.2 *Impulse and duration time for 50 per cent lethality*

Figure 8.3 also illustrates a similar relationship for primary deaths caused by whole body translation. Glasstone and Dolan describe experimental work on this mode using animals and dummies and propose a scaling law:[7]

$$d = d_r \times W^{0.4}$$

where d = distance for 50 per cent casualties;
W = mass of explosive in kilotonnes;
d_r = distance for a 1-kilotonne explosion.

The two curves are almost identical, and can be represented by the following formula. It can be regarded as the 50 per cent lethality contour for primary blast deaths, giving the distance in terms of the primary independent variable, explosive mass.

$$L = \frac{2 \times 10^{-2} \times T^{1/3}}{[1 + (20/T)^2]^{1/6}}$$

where T is explosive mass (tonnes) and L is distance (km).

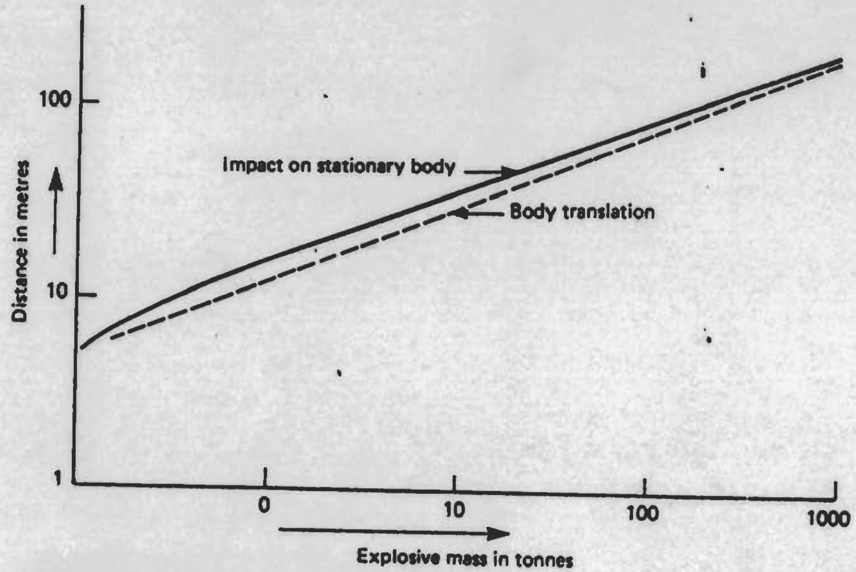


Figure 8.3 *Point source explosions primary blast deaths 50 per cent fatality to 70 kg man*

ESPLOSIONI

- FERITE DA MISSILI E FRAMMENTI

$$Pr = -27.1 + 4.26 \ln J \qquad J = \text{impulso } [N\,s/m^2]$$

TIPO DI MISSILE	ORGANO O EVENTO CRITICO	VELOCITÀ RELATIVA DI IMPATTO [ft/s]
Oggetto da 5 Kg non penetrante	<u>Danno cerebrale</u>:	
	Soglia di sicurezza	10
	Soglia danno probabile ...	15
	<u>Frattura spina dorsale</u>:	
	Soglia di sicurezza	10
	soglia di danno probabile ...	15
	soglia di danno certo	23
Frammenti di vetro da 10 g.	<u>Abrasione dell'epidermide</u>	
	Soglia di danno probabile ...	50
	<u>Ferite gravi</u>:	
	Soglia di danno	100
	Soglia prob. danno 50%	180
	Soglia di danno certo --	300

ESPLOSIONI

- FERITE DA TRASLAZIONI E COLLISIONI DEL CORPO CON OSTACOLI.

$$Pr = -39.1 + 4.45 \ln J \quad J = \text{impulso } [J\,s/m^2]$$

FERITE MORTALI

Probabilità di morte %	IMPULSO $N\,s/m^2$
1	18000
8	28600
31	37300
63	45100
86	49700
100	60800

ESPLOSIONI

- DANNI ALLE COSE

SOVRAPRESSIONE KPa	DANNO
1	Fessurazione vetri
3	Rottura vetri 100%
4.8	Danni strutturali minori
13.8	Collasso parziale murature
17.3	Distruzione 50% delle case
27	Rottura serbatoi
48	Distruzione completa delle case
70	Distruzione macchinari pesanti

TABELLA N - CORRELAZIONE SOVRAPRESSIONE - DANNI

STRUTTURA E TIPO DI DANNO	SOVRAPRESS. bar
rottura vetri delle finestre (50%)	0,025
rottura vetri delle finestre (75%) - danneggiamento telai finestre	0,05
danneggiamento della strumentazione di processo, di pannelli leggeri o lamierini	0,1
danneggiamento torri di raffreddamento, serbatoi di tipo atmosferico a tetto fisso, canale e condotte di ventilazione	0,14÷0,17
deformazione tubazioni e serbatoi atmosferici; rottura strumentazione di processo, pannelli/elementi in calcestruzzo leggero; danni ad edifici in muratura	0,2÷0,24
deformazione macchine, filtri, ecc.; spostamento tubazioni dai supporti; rottura serbatoi atmosferici	0,25÷0,28
deformazione mantello di apparecchi di processo NON a pressione (colonne di frazionamento-ecc.); deformazione muri in calcestruzzo (20 cm); rottura muratura in laterizio	0,35÷0,38
valore di soglia per danni gravi ai timpani	0,4
deformazione serbatoi a pressione orizzontali; rottura tubazioni	0,42÷0,45
danni gravi ad apparecchi di processo (rottura del mantello, spostamento da supporti di apparecchi leggeri - ecc.)	0,47÷0,49
danneggiamento serbatoi sferici a pressione ; rottura di muratura in calcestruzzo non rinforzato	0,53÷0,56
deformazione strutture portanti in acciaio ; spostamento dai basamenti di apparecchi (pompe, scambiatori, ecc.)	0,7

VULNERABILITÀ

IRRAGGIAMENTO

$$X \equiv \int_0^t k E^\alpha dt$$

DANNO

- USTIONI di vario grado

→ PER LE USTIONI MORTALI ←

FIREBALL (no evacuazione)

$$Pr = -14.9 + 2.56 \ln (t I^{4/3} / 10^4)$$

I = intensità efficace [J/m²/s]
t = durata [s]

POOL-FIRE e JET-FIRE (possibile evacuazione)

ip: - intensità della radiazione cost. nel tempo
- energia termica ricevuta funzione della distanza.

$$X \equiv \int_0^T K E^\alpha (y) dt \quad \text{ove} \quad T = (y_1 - y_0)/v$$

e v = velocità di fuga (costante)

con y_0 = distanza iniziale del soggetto

y_1 = distanza a cui l'incendio è sopportabile indefinitamente

IRRAGGIAMENTO

→ PER USTIONI DI I° GRADO ←

non esistono ancora probit.

esistono dosaggio di soglia.

$$R = t\, I^{1.15} = 550.000 \ J/m^2/s$$

dose di irraggiamento che causa ustioni di I° grado alla popolazione colpita.

→ DANNI ALLE PROPIETÀ (OGGETTI) ←

MODELLI (ALGORITMI) ON/OFF RISPETTO A VALORI LIMITE.

I_L e T_L = IRRAGGIAMENTO LIMITE e DURATA LIMITE PER CUI SI HA DISTRUZIONE

I_E e T_E = VALORI PRESENTI

SE $I_E > I_L$ e $T_E > T_L$ ⇒ DANNO

— PER IL LEGNO ←

$I_L = 2.54 * 10^4 \ J/m^2 s$

$T_L = [6.1 \times 10^4 / (I_E - I_L)]^{5/4}$

} POOL/JET FIRES

$I_L = 1.34 \cdot 10^4 \ J/m^2 s$

$T_L = [7.22 \times 10^5 / (I_E - I_L)]^{3/2}$

} FLASH-FIRES

IRRAGGIAMENTO

TIPO DI DANNO	IRRAGGIAMENTO [KW/m²]	
- STRUTTURE IN CALCESTRUZZO	60	KW/m²
- ACCIAIO e CALC. PRECOMPRESSO	40	"
- IGNIZIONE SPONTANEA DEL LEGNO	33	"
- DANNO AI SERBATOI	12.6	"
- DANNI AI CAVI AEREI	11.7	"
PERSONE		
- PERSONALE PROTETTO	5.	"
- PERSONALE NON PROTETTO	1.4	"

Irraggiamento

I valori degli Indici di Esposizione che si propongono distintamente valutati per le persone (EiP) e per le strutture (EiS), riferiti al flusso termico per una durata di esposizione pari a circa 30 secondi, sono quelli riportati nella tabella 12.

TABELLA 12

INDICI DI ESPOSIZIONE PER L'IRRAGGIAMENTO

Flusso termico (kW/mq)		Persone	Strutture
E3P	1.5	nessun effetto significativo	
E2P	3.0	primi effetti di ustioni significative	
E1P	5.0	primi effetti di mortalità	
E3S	10.0		fusione di materie plastiche, cavi
E2S	25.0		ignizione del legno
E1S	35.0		danni alle strutture metalliche

Esplosione

I valori dell'Indice di Esposizione riferiti all'onda d'urto comprendente i valori dell'impulso, riferiti ad un tempo di 100 ms, sono riportati nella tabella 13.

TABELLA 13

INDICI DI ESPOSIZIONE PER L'ESPLOSIONE

Sovrapressione			Persone	Strutture
	(Pascal)	(mbar)		
E3P	1000	10	nessun effetto	
E2P	5000	50	rottura dei timpani	
E1P	14000	140	lesioni ai polmoni (mortalità)	
E3S	1500	15		rottura vetri al 50%
E2S	6000	60		deformazione tubazioni e cedimento muri
E1S	30000	300		deformazione serbatoi, danni gravi a tubazioni

TABELLA 12

Indicazioni dei valori di riferimento per l'irraggiamento

Flusso termico (kW/mq)	Persone	Strutture
1.5 , 1.6	Soglia massima ammissibile per esposizioni prolungate (nessuno scompenso anche dopo lunga esposizione)	-
3.0	Primi effetti di ustioni significative	-
4.5 , 4.7	Soglia massima ammissibile di ustioni per esposizioni di circa 20"	-
5.0	Primi effetti di mortalità	-
10 , 12.5	Ustioni di 1° grado in 10", 1% di mortalità in 30"	Fusione di materiali plastici, cavi, verniciature; Ignizione di carta-cartone; Ignizione pilotata del legno
25	Ustioni di 2° grado in pochissimi secondi	Ignizione del legno dopo esposizione prolungata
37.5	1% di letalità in 10" 100% di letalità in 60"	Danneggiamento di materiali metallici e di apparecchiature

VULNERABILITÀ

SOSTANZE TOSSICHE

La vulnerabilità dell'uomo alla inalazione di sostanze tossiche è legata a:

- natura della sostanza inalata
- durata della inalazione
- concentrazione della sostanza tossica.

$$D = \int_0^T C(t)^n \, dt$$

D = dosaggio

T = durata totale dell'inalazione

$C(t)$ = concentrazione tossica

n = coeff. tipico della sostanza.

La Probit x mortalità (o l'ospedalizzazione)

$$Pr = a + b \ln \int_0^T C(t)^n \, dt$$

che è valido nel caso di soggetto fermo

SOSTANZA	a	b	n
CLORO	-17.1	1.69	2.75
AMMONIACA	-30.5	1.38	2.75

statistical distributions relating the probability of injury to the dose (total intake). Typically this is a log-normal distribution but for these purposes can take the form of a probit equation which relates the effect of an exposure to a given concentration and duration.

The general form of a probit equation is:

$$P_T = a + b \log_e (C^n t)$$

where:

P_T is a measure of the percentage of people affected;
a, b, and n are constants;
C = concentration (ppm);
t = exposure time (min).

The quantity (C^n t) is known as the toxic load.
Table 3.4 [d] gives the constants for the lethal toxicity probit equation for a number of the more common chemicals.

Hence, for:

- Chlorine: $P_T = -8.29 + 0.92 \log_e (C^2 t)$
- Ammonia: $P_T = -35.9 + 1.85 \log_e (C^2 t)$

A probit (P) is a probability unit lying between 0 an 10, which is directly related to the % fatalities as shown in Tab. 3.5. To evaluate the probit, the toxic load (C^n t) must be calculated at positions of interest. At a given location the concentration will vary over time as the cloud passes and dilutes. The total toxic load for the location is obtained by considering different time steps and the average concentration during those time steps. Then for m time steps the total toxic load is given by:

$$\text{Total Toxic Load} = \sum_{i=1,m} (C_i^n t_i)$$

This total toxic load is then used in the probit equation.

The important factor is the determination of the effects of toxic material is to clearly study the known data about the material in question. These include the MHAP monographs for Chlorine, Ammonia and Phosgene, publications by

TABELLA 17

Valori dei parametri per l'equazione di Probit (E3P)

Sostanza	A	B	n
Acido solfidrico	-31.42	3.008	1.43
Acrilonitrile	-29.42	3.008	1.43
Acroleina	-9.931	2.049	1
Ammoniaca	-35.9	1.85	2
Biossido di azoto	-13.79	1.4	2
Biossido di zolfo	-15.67	2.1	1
Bromo	-9.04	0.92	2
Cloro	-8.29	0.92	2
Formaldeide	-12.24	1.3	2
Isocianato di metile	-5.642	1.637	0.653

SOSTANZE TOSSICHE

CRITERI

Simbolo		Ente
IDLH esp x 30min	immediately dangerous to life or health —o— National Institute for Occupational Safeti and health	NIOSH
EEGLs 1-24 ore di intervento	Emergency Expouse Guidance levels	
SPEGLs 10-50% inf degl. EEGL	Short-Term Public EEGLs —o— National Academy of Sciencs / National Research Coulcil	NAS/NRC
TLV TLV-TWA	Threshold Limit Values conc media in 8 ore di lavoro giornaliero	
STEL TLV-STEL	Short-Term Expoosure limits and ceiling concentration (15 min di conc. max) erogazione in 30 min —o— American Conference of Governmental Industrial Hygienists	ACGIH
PEL come TLV-TWA	Permessible Expoure Limits —o— Occupational Safety and Health Administration	OSHA

PROBIT

SOSTANZE TOSSICHE

SOSTANZA	TLV-TWA mg/m³	TLV-STEL mg/m³
Acetone	1747	2336
Acetilene	5316	5316
Acido cloridrico	7.3	7.3
Ammoniaca	12.5	18.8
Benzene	31.4	31.4
Cloro	1.5	3
Cloruro di vinile	12.7	12.7
Formaldeide	2	6
Esano	173	173
Diclorometano	1738	347
Anidride carbonica	8834	53000

CONVERSIONE

$$mg/m^3 = ppm \frac{M}{24.45}$$

M = peso molecolare

24.45 = volume in litri di una grammomolecola.

Table 9.13 Probit equations for some major hazards (after Eisenberg *et al.*, 1975)
(Courtesy of the U.S. Coast Guard)

Phenomenon and type of injury or damage	*Causative variable*	*Probit equation parameters* k_1	k_2	*Data from which the probit equation was derived* per cent affected	value of variable	per cent affected	value of variable	per cent affected	value of variable
Fire:									
Burn deaths from flash fire	$t_e I_e^{4/3}/10^4$	−14.9	2.56	1	1099	50	2417	99	7008
				1	1073	50	2264	99	6546
				1	1000	50	2210	99	6149
Burn deaths from pool burning	$tI^{4/3}/10^4$	−14.9	2.56	1	1099	50	2417	99	7008
				1	1073	50	2264	99	6546
				1	1000	50	2210	99	6,49
Explosion:									
Deaths from lung haemorrhage	p^o	−77.1	6.91	1	1.00×10^5	50	1.41×10^5	99	2.00×10^5
				10	1.20×10^5	90	1.76×10^5		
Eardrum ruptures	p^o	−15.6	1.93	1	16.5×10^3	50	43.5×10^3		
				10	19.3×10^3	90	84.3×10^3		
Deaths from impact	J	−46.1	4.82	0	18.0×10^3	31	37.3×10^3	96	49.7×10^3
				8	28.6×10^3	63	45.2×10^3	100	60.7×10^3
Injuries from impact	J	−39.1	4.45	1	13×10^3	90	28×10^3		
				50	20×10^3				
Injuries from flying fragments	J	−27.1	4.26	1	1024	50	1877	99	3071
Structural damage	p^o	−23.8	2.92	1	6.2×10^3	99	34.5×10^3		
				50	20.7×10^3				
Glass breakage	p^o	−18.1	2.79	1	1700	90	6200		
Toxic release:									
Chlorine deaths	$\Sigma C^{2.75} T$	−17.1	1.69	3	14.1×10^4	50	34.05×10^4	97	105.8×10^4
				3	17.0×10^4	50	47.0×10^4	97	129.4×10^4
				3	21.5×10^4	50	64.7×10^4		
Chlorine injuries	C	−2.40	2.90	1	6	50	13		
				25	10	90	20		
Ammonia deaths	$\Sigma C^{2.75} T$	−30.57	1.385	3	37.3	50	74.6	99	411.8
				3	90.9	50	204.6	99	334.4
				3	44.6	50	148.6		

Key:
t_e = effective time duration (s)
I_e = effective radiation intensity (W/m²)
t = time duration of pool burning (s)
I = radiation intensity from pool burning (W/m²)
p^o = peak overpressure (N/m²)
J = impulse (N s/m²)
C = concentration (ppm)
T = time interval (min)

Valori di riferimento per la valutazione degli effetti

Fenomeno fisico	Zone ed effetti caratteristici 1 Elevata probabilità di letalità	 2 Danni gravi a popolazione sana	Note
Esplosioni (sovrappressione di picco)	0,6 bar (0,3 bar)*	0,07 bar	1
BLEVE/Sfera di fuoco (radiazione termica variabile)	raggio fireball	200 KJ/m^2	2
Incendi (radiazione termica stazionaria)	12,5 kW/m^2	5 kW/m^2	3
Nubi vapori infiammabili	LFL	0,5 x LFL	4
Nubi vapori tossici	LC50	IDLH	5

Legenda

LFL Limite inferiore di infiammabilità

LC50 Concentrazione di sostanza tossica, letale per inalazione nel 50% dei soggetti esposti per 30 minuti.

IDLH Concentrazione di sostanza tossica fino alla quale l'individuo sano, in seguito ad esposizione di 30 minuti, non subisce per inalazione danni irreversibili alla salute e sintomi tali da impedire l'esecuzione delle appropriate azioni protettive.

* Per gli effetti indiretti rilevanti; applicabile in presenza di edifici o manufatti collassabili.