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Fire and explosion hazards to flora and fauna from explosives

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Abstract

Deliberate or accidental initiation of explosives can produce a range of potentially damaging fire and explosion effects. Quantification of the consequences of such effects upon the surroundings, particularly on people and structures, has always been of paramount importance. Information on the effects on flora and fauna, however, is limited, with probably the weakest area lying with fragmentation of buildings and their effects on different small mammals. Information has been used here to gain an appreciation of the likely magnitude of the potential fire and explosion effects on flora and fauna. This is based on a number of broad assumptions and a variety of data sources including World War II bomb damage, experiments performed with animals 30–40 years ago, and more recent field trials on building break-up under explosive loading. © 2000 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction:

In recent years, world attention has increasingly focused on environmental issues. A European Council Directive 'Control of Major Accident Hazards (COMAH) Involving Dangerous Substances', known as the 'Seveso II' Directive [1], has now been adopted in the UK by the COMAH 1999 Regulations [2]. For the first time, certain explosives manufacturing and storage sites are brought into the regulatory arena for general chemicals, with associated requirements for such things as safety reports for top tier sites and the preparation of major hazard accident prevention policies. Greater emphasis is also placed on protection of the environment, and COMAH will require for example, assessment of the toxic, fire, and explosion threats to flora and fauna on and surrounding

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the site. This paper is directed towards quantifying the potential fire and explosion effects on flora and fauna from accidentally initiated explosives.

2. Major accidents:

The COMAH Regulations defines ‘major accident’ as ‘an occurrence (including in particular, a major emission, fire, or explosion) resulting from uncontrolled developments in the course of the operation of any establishment, and leading to serious danger to human health or the environment, immediate or delayed, inside or outside the establishment, and involving one or more dangerous substances’. Schedule 7 sets out the criteria for the notification of major accidents to the Commission, viz,

(i) permanent or long term damage to terrestrial habitats:
- ♦ 0.5 ha or more of a habitat of environmental or conservation importance protected by legislation (which equates to a circular plot of land of radius 40 m),
- ♦ 10 ha or more of more widespread habitat including agricultural land (which equates to a circular plot of land of radius 179 m);

(ii) significant or long term damage to freshwater and marine habitats:
- ♦ 10 km or more of river or canal,
- ♦ 1 ha or more of a lake or pond,
- ♦ 2 ha or more of a delta,
- ♦ 2 ha or more of a coastline or open sea;

(iii) significant damage to an acquifer or underground water; — 1 ha or more.

The first category of potential accidents affecting habitats is the most relevant for explosives.

3. Potential fire and explosion hazards to flora

3.1. Fireball hazards

Associated with the detonation of an explosive is a fireball. All flora within the fireball radius is at risk of ignition, with possible subsequent propagation to the surrounding flora. The dimension of such a fireball is given [3] by:

$$D = 8.5 \times W^{0.341}$$

where D = diameter of fireball in feet and W = weight of explosive in pounds

For 50 t/50.8 T of high explosives for example, $D = 8.5 \times 112{,}000^{0.341} = 448$ ft (137 m); i.e. all flora within a radius of 68 m are at risk of ignition with possible subsequent propagation to surrounding flora.

3.2. Blast overpressure and fragment hazards

Trees are sensitive to drag forces, such as wind from the blast wave. Deciduous broad-leaved trees will be much more sensitive to drag forces than coniferous trees. In general, tree strength will depend on type, girth, type of ground/soil, and drainage.

During and just after World War II, the UK government's 'Ministry of Home Security' did much to catalogue and analyse the effects of German bombings. One such analysis reported in a paper [4] was concerned with the effects of bomb blasts on trees and undergrowth. Several bomb explosions in woods containing oaks, hazel, sycamore, beech, etc., were studied against four categories of damage.

Category 1: ground completely cleared, all trees either uprooted or snapped off near the root, leaving stumps not exceeding 6 ft in height.
Category 2: trees heavily damaged, with trunk or major branches broken off; the limit of this area will be fixed by the distance at which trees are structurally complete, though minor twigs and leaves are removed.
Category 3: trees have lost twigs and leaves only; the limit of the area will be fixed by the distance at which leaves remain on the trees at all levels, although they may be torn by the blast; it will usually be found that some leaves will remain on the upper branches of a high tree, almost up to the limit of Category 2, but this will not count for this purpose.
Category 4: undergrowth, bracken, etc., uprooted or sufficiently badly damaged to cause fading.

The incidents analysed involved five separate 1750 lb FLY bombs; a cluster (16) of 500 lb bombs, and one incident involving 20,000 lb of nitrostarch. The paper gives graphs of the radius of damage versus charge weights for the four levels of damage (see Fig. 1). No equations for these are given, but the paper reports that the type of damage may be expected to be of the form

$$\text{Radius } R = \text{constant} \times W^{0.425}$$

where R is in feet, and W is in pounds.

Equations of this form which provide a good fit to the four category of damage curves are provided by constants 1.813 (Category 1), 2.586 (Category 2), 3.864 (Category 3), and 5.154 (Category 4), respectively.

Dr. Norman Scilly [5] reworked this same information taking account of bomb casing factors and revised TNT-equivalences, as shown in Table 1.

This work compares well with the results of a surface detonation of a hemispherical charge of 50 t/50.8 T of TNT in a managed coniferous forest [6] (pine, spruce, and fir) as follows:

- ♦ at 207 m (680 ft), all of the trees standing and only a few limbs (mostly knocked off by ejecta) on the ground;
- ♦ at 146 m (478 ft), more limbs down;

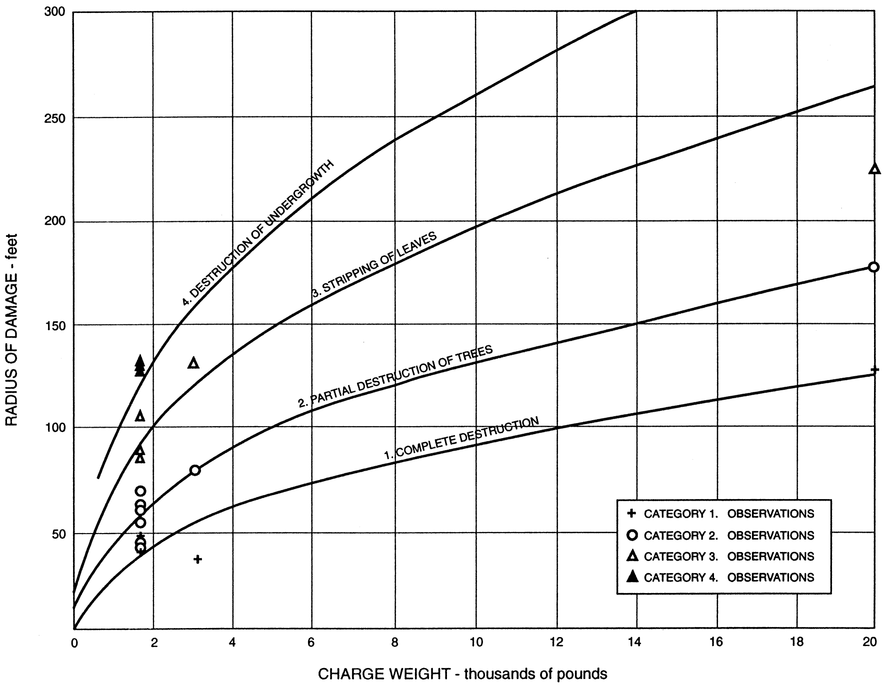

Fig. 1. Radius of Damage to Trees and Undergrowth versus Charge Weight.

- ♦ at 116 m (381 ft), some trees down and some leaning over, supported by trees still standing;
- ♦ at 110 m (360 ft), most of the trees down;
- ♦ at 99 m (326 ft), all trees down and a high concentration of needles;
- ♦ at 79 m (260 ft), the area has a more stripped appearance, with at least some of the branches blown downwind.

The measured blast wave parameters in Table 2 show significant modification to expectation due to interactions with the forest. Fragmentation effects on trees and undergrowth are included to some extent in Tables 1 and 2 above, but will not include the effects of additional debris which would be generated from a similar detonation

Table 1
Tree damage/distance relationships

Category of damage	Radius (m) [W is weight in kg]	Radius for 50 t/ 50.8 T of TNT	
		(m)	(ft)
1	$0.84W^{0.440}$	99	324
2	$1.39W^{0.426}$	141	461
3	$2.10W^{0.419}$	197	645
4	$2.65W^{0.421}$	253	832

Table 2
Tree blown down from 50 t/ 50.8 T of HE [6]

Range		Overpressure (measured)		Number blown down	Percentage
ft	m	psi	kPa		
220–280	67–85	29–18	200–124	20/20	100
283–330	86–101	18–14	124–96	23/23	100
331–462	116–141	14–11	96–76	15/17	88
380–462	116–141	11–9	76–62	7/13	23
660–700	201–213	6	41	0	0

inside a brick/concrete storage magazine. There is insufficient information at this time on these latter effects to allow their proper quantification.

4. Potential fire and explosion hazards to fauna

4.1. Fireball hazards

Certain species of animals spend some of their time underground, and their overall vulnerability to fireball/thermal radiation hazards will therefore depend upon their location at the time of the incident. Any risk assessment will clearly need to take due cognisance of this. It is assumed that all animals below ground will be safe from the short duration fireball effects associated with an explosion. For animals above ground, it is assumed that if they are within the fireball radius, they will be killed. Using the 50 t of high explosives example given earlier (Section 3.1), it is assumed that all animals within the fireball radius of 68 m and above ground will be killed.

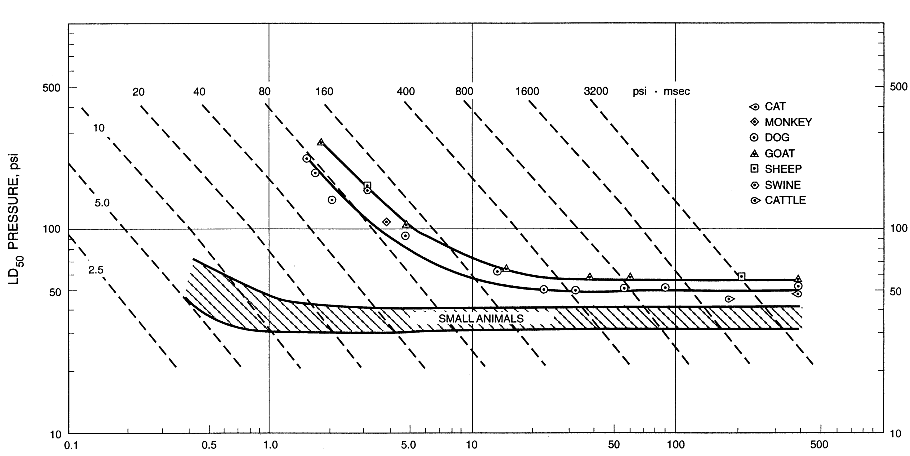

Fig. 2. The Pressure-Duration Relationship and Lethality for Large and Small Animals (mice, hamsters, rats, guinea pigs and rabbits).

Table 3
Twenty-four-hour LD_{50} and probit regression constants for animals exposed to short duration (2.1–4.6 ms) reflected shock waves [8]

Species and number	Mean body weight	LD_{50} (psig)	Duration (ms)	Probit equation constants	
				Intercept a	Slope b
Mouse 120	22.2 g	25.9 (24.8–27.0)	2.1	−19.639	17.428
Rat 40	205 g	35.8 (33.4–38.3)	3.6	−22.074	17.428
Guinea pig 82	568 g	31.4 (29.6–32.9)	3.8	−21.080	17.428
Rabbit 70	2.0 kg	38.2 (36.3–40.3)	3.6	−22.563	17.428
Monkey 12	5.7 kg	111 (97–128)	3.6	−30.659	17.428
Dog 29	16.0 kg	88.2 (80.9–96.8)	4.6	−28.908	17.428
Goat 15	22.7 kg	107 (96–119)	4.4	−30.352	17.428
Sheep 57	53.3 kg	167 (159–176)	2.9	−33.721	17.428
Swine 16	55.6 kg	154 (138–170)	2.9	−33.113	17.428

Notes: LD_{50}s are to 90% confidence limits; standard error of the slope constant + / − 2.371 ambient pressure = 12 psia; probability of fatality (%) in Probit Units = $a + b \log P$, where P = reflected overpressure, psi.

4.2. Explosion hazards

4.2.1. Primary blast injuries

For animals below ground, it is assumed that provided they are outside the crater radius, they will be safe from direct blast effects. It is assumed that animals within the radius of catering will be killed. A simple approach [7] for estimating crater dimensions, use the formula

$$\text{Apparent Crater Radius (m)} = kM^{0.33}$$

where M is the weight of TNT in kg, and $k = 0.2$ for very hard, and 0.7 for very soft ground.

World War II and later studies of blast induced injuries to animals determined that the most common form of lethal injury was through lung hemorrhage. Also, the amount

Table 4
Transformation of percentages into probits.

Percentage	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	4.36	4.39	4.42	4.25
30	4.48	4.5	4.53	4.56	4.59	4.61	4.64	4.67	4.69	4.72
40	4.75	4.77	4.8	4.82	4.85	4.87	4.9	4.92	4.95	4.97
50	5	5.03	5.05	5.08	5.1	5.13	5.15	5.18	5.2	5.23
60	5.25	5.28	5.31	5.33	5.36	5.39	5.41	5.44	5.47	5.5
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
99 + %	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	7.65	7.75	7.88	8.09

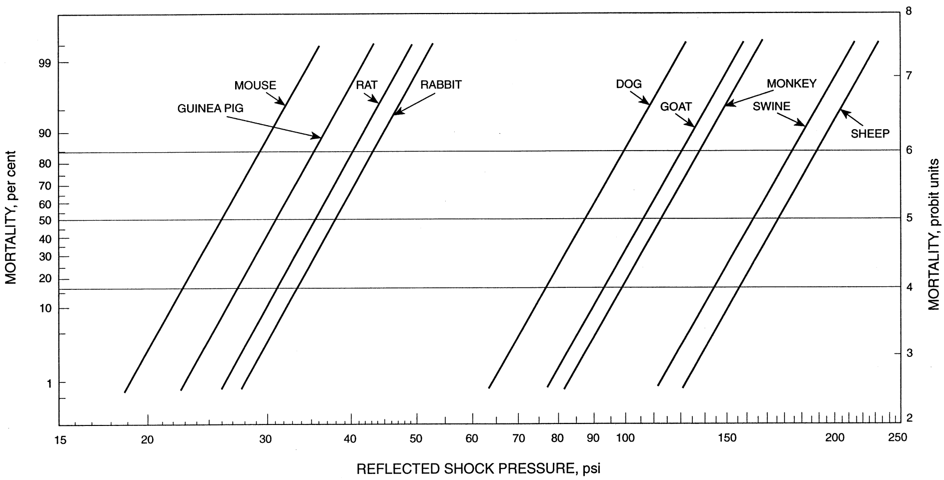

Fig. 3. Mortality Curves for Animals Exposed to ''Short''-Duration Reflected Pressures from High-Explosive Charges Detonated Overhead While Mounted Prone on a Concrete Pad.

of damage was inversely proportional to the cube root of the body weight of the animal and duration of the shock wave [8] (see Fig. 2 appended). Mortality information 'for animals exposed to short duration (2.1–4.6 ms) reflected overpressures from high explosives charges detonated overhead while mounted prone on a concrete pad' is given in Tables 3 and 4 and Fig. 3.

In Fig. 3, the steep slopes of the lines indicate a relatively small range of pressure dose from LD_1 to LD_{99} levels, which the original authors of the paper describe as ''a sort of 'all-or-none' type response''. For mammals exposed to shock waves of 180–400 ms durations [8] and the 24-h mortality rates are given in Table 5 and Fig. 4.

The detonation for example of a 50 t/50.8 T magazine of high explosives would produce 1%, 50%, and 99% mortality rates for mouse, cat, and sheep at distances as given in Table 6.

Table 5
Twenty-four-hour LD_{50} and probit regression constants for animals subjected to long duration reflected pressures

Species and number	Mean body weight (g)	LD_{50} (psig)	Duration (ms)	Probit equation constants	
				Intercept *a*	Slope *b*
Mouse 200	20.7	26.7 (25.5–28.0)	339	−17.07	15.47
Hamster 110	89.2	28.6 (27.1–30.0)	361	−17.51	15.47
Rat 150	200	30.4 (29.1–31.7)	340	−17.93	15.47
Guinea pig 120	424	25.9 (24.7–27.2)	342	−16.86	15.47
Rabbit 40	3.7	24.8 (22.6–27.3)	351	−16.56	15.47
Cat 48	2.5	43.6 (40.3–47.3)	368	−20.36	15.47
Dog 35	15.1	47.9 (44.0–52.3)	414	−20.99	15.47
Goat 30	20.5	52.8 (48.0–58.1)	412	−21.64	15.47
Sheep 39	63.6	54.9 (50.7–59.6)	212	−21.9	15.47
Cattle 27	180	42.7 (38.7–47.0)	184	−20.21	15.47

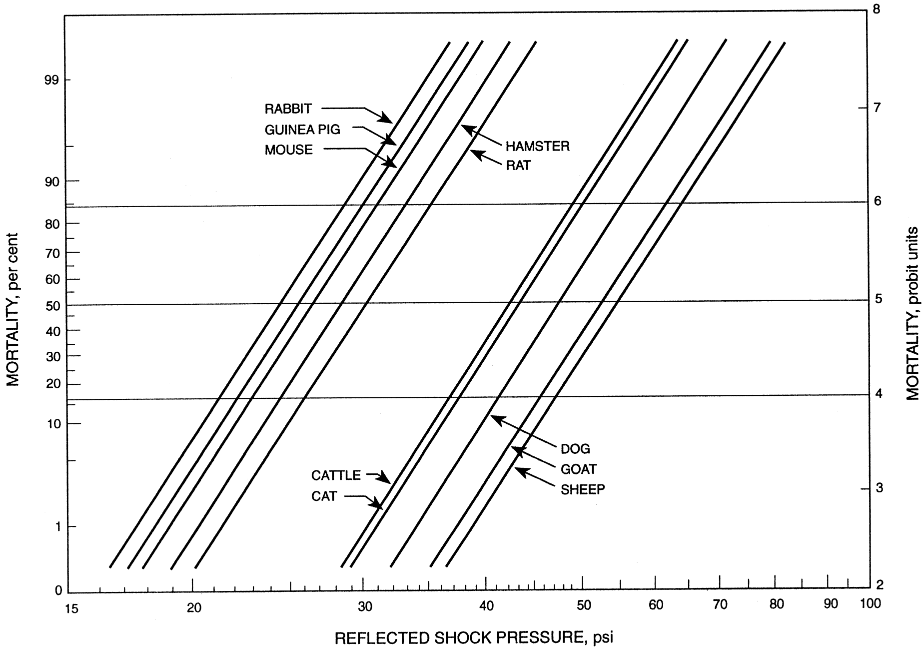

Fig. 4. Mortality Curves for Animals Exposed to ‘‘Long’’-Duration Reflected Pressures While Mounted Side-On Against the Endplate of a Shock Tube.

4.2.2. Fragmentation effects

In the 1980s, the UK’s Ministry of Defence (ESTC) conducted a series of trials in Australia [9], to determine the explosion effects from 500–5600 kg of explosives in brick and reinforced concrete traversed buildings, and 75,000 kg in a standard ‘igloo’ construction. Such work gives a useful indication of the damage and possible injury which might be realised in the event of an uncontrolled explosion. More recently, trials have been conducted both on small quantities (10–50 kg) of high explosives held in brick and concrete magazines [9], and on small quantities (75 and 450 kg) of blasting explosives in steel magazines. The work on brick/concrete magazines has shown significant fragmentation hazards result mainly from the storage building themselves. Much work remains to be done on quantifying the numerous variables, which include

Table 6
Distances to 24-h mortality rates at distance from 50 t/50.8 T of HE

Species	Mortality rate distances (m) from 50 t of TNT		
	1%	50%	99%
Mouse	153	140	122
Cat	124	115	101
Sheep	114	106	93

Table 7
Distances to human fatality probabilities from 50 t/50.8 T of HE inside a brick/concrete magazine

Distance (m)	Average fatality probability
200	0.24
150	0.40
125	0.51
100	0.66
75	0.84
60	0.98

the nature of the containment building, the explosives loading density, and the explosives stand off distance. The fragmentation effects from the steel magazine trials have not been fully analysed as yet, but are less than those from the brick and concrete structures. A very crude analysis of the brick and concrete fragment throw data [10] suggests that

$$\text{the average fatality probability for humans} = 0.286 \ln[0.01Q] \cdot e^{-0.01D}$$

where Q = quantity of TNT (kg), up to 75,000 kg; D = distance/range (m)

The criteria for 'potentially lethal' debris in this analysis is based on the generally accepted criterion of debris with energy of or greater than 80 J. Coupled with the typical range of velocities (tens of metres per second) exhibited by building debris allows a 'potentially lethal' (to humans) minimum debris weight of 100 g to be calculated. For brick or concrete, this approximates to a 50 mm cube. This allowed the use of simple weighing or sieving techniques to be used on site for sorting. The raw data was then analysed in accordance with the Pseudo-Trajectory Normal (PTN) Method [11], which accounts for debris passing through any debris collection zone, in addition to debris landing in that zone. The 1% lethality equates to one fragment landing in/passing through a 55.7 m^2 area of ground. This assumes a human 'target' area of vulnerability of 0.56 m^2. Using the above equation to calculate the average fatality probabilities for humans at distance from the detonation of 50 t (50.8 T) of high explosives in an above ground brick/concrete magazine gives results as presented in Table 7.

Table 8
Impact velocity/mortality estimates for four animal species

Species of animals	Impact velocities, ft/s (computed for 95% confidence intervals)			Probit equation constants		
	LD_{10}	LD_{50}	LD_{90}	a (intercept)	b (slope)	$S(b)$
Mouse	32.3 (27.2–34.6)	39.4 (37.4–42.0)	47.9 (44.1–59.4)	−18.86	14.96	3.02
Rat	37.4 (34.2–39.3)	43.5 (42.0–44.8)	50.7 (48.7–54.2)	−26.73	19.36	2.76
Guinea pig	27.7 (25.4–28.9)	31.0 (30.0–31.9)	34.7 (33.5–37.4)	−33.84	26.04	4.49
Rabbit	28.8 (25.0–30.3)	31.7 (30.2–33.3)	35.0 (33.3–40.1)	−40.97	30.61	7.08

Note: $-S(b)$ is the standard error slope constant.

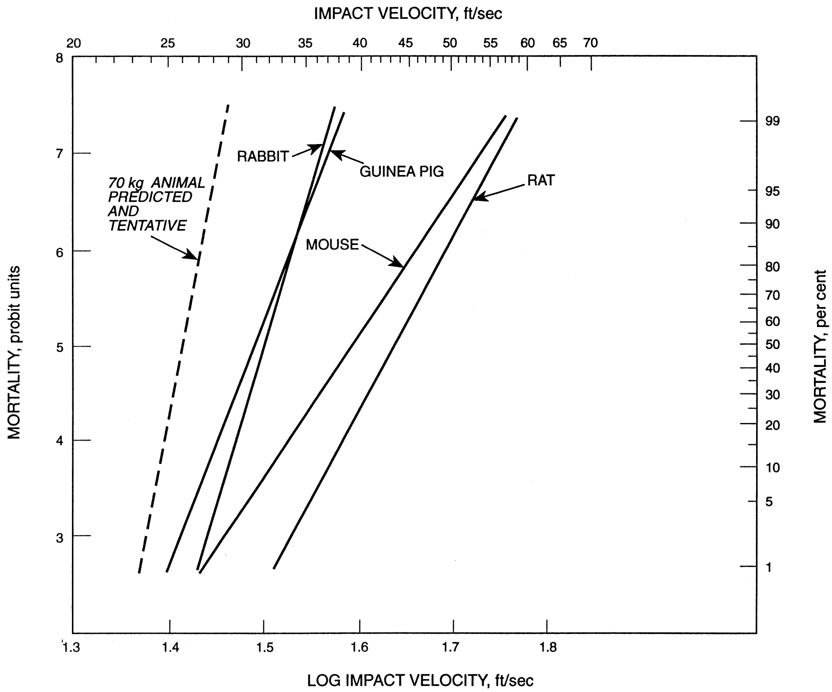

Fig. 5. Comparison of Probit Mortality Curves.

Little information is available on the effects of fragments on fauna. A very crude indication of the corresponding potential fragmentation effects on fauna can be obtained by factoring down the predictions gained from the above equation by the appropriate reduced ‘target’ area of the mammal. For a small dog, for example, the average fatality probability will be roughly a quarter of the values predicted by the above equation. This assumes that the mammal in question is equally vulnerable to missile/fragment attack as humans. For very small mammals, the inaccuracy of this approach will be greatly magnified for a number of reasons, including that the lethal fragment energy is likely to

Table 9
Maximum translational velocities from 50 t/50.8 T of TNT

Incident overpressure	Maximum velocities (ft/s) from 50 t/50.8 T source			
	Mice	Rats	Guinea pigs	Rabbits
1 atm/14.7 psig	130	77	60	36
1.5 atm/22.1 psig	180	115	90	48
2 atm/29.4 psig	230	140	115	63
2.5 atm/36.8 psig	275	170	140	75
3 atm/44.1 psig	315	190	160	90
4 atm/58.8 psig	400	240	205	115

Table 10
Distances from 50 t TNT source and corresponding lethality probabilities

Species	Distances from 50 t source and corresponding lethality probabilities								
	LD_{10}			LD_{50}			LD_{90}		
	Velocities ft/s	Overpressure (psig)	Distance from source (m)	Velocities ft/s	Overpressure (psig)	Distance from source (m)	Velocities ft/s	Overpressure (psig)	Distance from source (m)
Mice	32.3	3.4	269	39.4	4.4	229	47.9	5.1	209
Rat	37.4	6.8	177	43.5	8.1	161	50.7	9.4	148
Guinea pig	27.7	6.5	181	31	7.4	169	34.7	7.9	163
Rabbit	28.8	12	131	31.7	13.3	122	35	14.7	118

be much less than 80 J, and in the building debris trials referred to above, fragments of less than 100 g or approximating to a 50 mm cube were not collected.

4.2.3. Translational injuries

Tertiary injuries arise from whole body translations where victims are thrown around bodily. Injuries caused solely by accelerative forces associated with such movements are considered to be insignificant compared with those associated with 'deceleration', i.e. impact with a hard unyielding surface! Mortality curves from experiments carried out [12] with four different animal species to determine the impact velocities are presented in Table 8 and Fig. 5, with results from a Probit analysis as follows.

Calculations of the incident blast overpressures corresponding to the blast-induced translational velocities given in columns 2–4 of Table 8, are possible using a methodology outlined in Ref. [13]. By this approach, acceleration coefficients of 0.38, 0.19, 0.15, and 0.079 ft^2/lb, respectively, for mice, rats, guinea pigs, and rabbits can be used to read off maximum translational velocities, etc., from graphs based upon an explosion source of 1 T of TNT. Note: acceleration coefficient = [(area presented by object) × (drag coefficient)]/[mass]. To estimate the maximum translational velocities for a larger source of blast, the acceleration coefficients are scaled/factored by $[2 \times \text{quantity of TNT in tons}]^{0.333}$, and maximum translational velocities can then be read off the appropriate incident blast overpressure graph. For 50 t/ 50.8 T of TNT, the maximum translational velocities are as follows Table 9.

The corresponding distances from the detonation of 50 t of HE at which 1%, 50%, and 90% lethalities occur are given in Table 10.

5. Summary and conclusions

An attempt has been made to quantify the potential fire and explosion threats to flora and fauna from accidentally initiated explosives. Such information is of general use, but more specifically may assist both in the preparation and assessment of COMAH Safety Reports. Site-specific assessments will need to consider the possibilities of such things as the time spent underground by certain fauna, reflected shock wave interactions from hard reflecting surfaces, and translational impacts of species onto the same hard unyielding surfaces. The areas of greatest uncertainty lie with the prediction of potential fragmentation characteristics of the explosives storage building, and the resultant fragmentation effects on the fauna. Little information is available at this time on these matters.

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