

# **A Model for Injury from Fragments Generated by the Explosion of Munitions**

by S.M.Gilbert,F.P.Lees and N.F.Scilly  
Department of Chemical Engineering,Loughborough University of  
Technology,Loughborough,  
Leicestershire LE11 3TU,UK

A model is described for the assessment of the injury to persons exposed in the open to primary fragments generated by the explosion of a stack of munitions. The model is in two parts,the first dealing with the generation and flight of the fragments and the second with their injuring power. The model accepts standard fragment mass distribution data for the unit of weapons. It generates the probabilities of fatal,severe and slight injury as a function of distance.

## **Introduction**

This paper describes a model for injury from primary fragments generated by the explosion of a stack of munitions. The model may be used as a free-standing one or as a sub-model within the overall model for the hazard assessment of the explosion of a vehicle carrying explosives in a built-up area,whih is described in a companion paper<sup>1</sup>. A computer program based on,and numerical results from,this model are also described.

The explosion of a cased explosive,or weapon,in a built-up area will emit a large number of high velocity fragments. These fragments may cause injury to persons outdoors and possibly also to those indoors. A person indoors is less vulnerable due to the hard cover provided by the building walls. However,the number of people indoors is generally much greater so that it is not immediately obvious which type of exposure will have the largest overall number of casualties by this mode. The primary fragment hazard is of particular importance for scenarios in which a large number of people are exposed outdoors,such as an explosion on a busy dockside.

## **Model for Hazard from Primary Fragments**

In the first instance,the model is described by considering the hazard presented by primary fragments from a single weapon. The account is later expanded to incorporate the effects associated with a stack of munitions.

A model for assessing the hazard from primary fragments may in principle be constructed in two parts,a model for the generation and flight of the fragments and one for the injuring power of the fragments. The construction of a model for fragment injury from first principles includes the following elements:

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## Generation of fragments

- Fragment mass distribution
- Fragment shape distribution
- Initial velocity of fragments
- Projection angle of fragments

## Flight of fragments

- Velocity of fragments vs distance

## Injuring power of fragments

- Penetration by fragments
- Injury by fragments

## Injury by fragments

- Number of fragments with injuring power
- Spatial density of fragments with injuring power
- Exposed area of human body
- Number of persons injured
- Vulnerable area

## ***Textbook of Air Armaments Method***

An early approach is that given in the *Textbook of Air Armaments* of the Ministry of Supply<sup>2</sup>, referred to hereafter as the *Textbook*. Although the method is old, it illustrates the main features of a fragment injury model and it includes the illustrative example of the British 20 lb bomb.

A more recent approach is that embodied in the FRAGHAZ program, referred to below.

## **Model for a Single Weapon**

For a single weapon the model may be summarised as follows. The relations selected for the model are the Held equation for the fragment mass distribution; the Gurney equation for the initial velocity of the fragments, with the relation of Kamlet and Finger for the Gurney constant; a uniform distribution of projection angles; equations from the *Textbook* and from Christopherson for retardation of fragments, in the supersonic and subsonic regimes, respectively; and the authors' own model for missile injury.

The behaviour of the fragments from the explosion is now considered; the injury which they cause is discussed later

## **Generation and Flight of Fragments**

### *Fragment Mass Distribution*

The fragment mass distribution (FMD) for a particular weapon may be obtained experimentally by initiating the weapon and collecting the fragments emitted. In some cases information is also obtained which gives estimates of the launch angle and initial velocity of

the fragments.

A method of correlating the FMD has been developed by Held<sup>3-5</sup>. The correlation is

### EQUATION

$$M(n) = M_0 [1 - \exp(-Bn^\lambda)] \quad (1)$$

where  $M(n)$  is the cumulative fragment mass, or overall mass of the fragments of number  $n$ , starting with the largest fragment;  $M_0$  the total mass of fragments;  $n$  the number of the  $n$ th largest fragment, or cumulative fragment number; and  $B$  and  $\lambda$  are constants.

The mass  $m$  of the  $n$ th fragment is obtained from equation (1) by differentiation

### EQUATION

$$m = \frac{dM(n)}{dn} = M_0 B \lambda n^{\lambda-1} \exp(-Bn^\lambda) \quad (2)$$

#### *Initial Velocity of Fragments*

For the initial velocity of the fragments use is made of the Gurney<sup>6</sup> equation for cylindrical geometries:

### EQUATION

$$u_0 = C_G \left[ \frac{C/M}{1 + (C/M)/2} \right]^{1/2} \quad (3)$$

with

### EQUATION

$$C_G = [2(-\Delta E)]^{1/2} \quad (4)$$

where  $C$  is the mass of explosive (kg),  $\Delta E$  the internal energy of explosion per unit mass of explosive,  $M$  the mass of the cylindrical section of the casing, and hence of the sidewall fragments (kg),  $u_0$  the initial fragment velocity (m/s), and  $C_G$  the Gurney constant (m/s).  $C_G$  is also commonly known as the Gurney velocity.

The Gurney constant has a unique value for any given explosive. Values for a number of the more common explosives are given by Kinney and Graham<sup>7</sup>. In the present work the Gurney constant is estimated using the general method proposed by Kamlet and Finger<sup>8</sup>:

### EQUATION

$$C_G = 0.887\phi^{0.5}\rho_0^{0.4} \quad (5)$$

with

### EQUATION

$$\phi = NM^{0.5}Q^{0.5} \quad (6)$$

where  $M$  is the average molecular weight of the products of explosion,  $N$  the number of mols of gas produced by the explosion,  $Q$  the heat of detonation (cal/g),  $\rho_0$  the explosive loading density ( $\text{g/cm}^3$ ) and  $\phi$  a parameter.

#### *Projection Angle of Fragments*

Relationships such as that of Taylor<sup>9</sup> exist for the projection angle of fragments from a single weapon. In practice, these models of projection angle appear of limited use in accident modelling where the appropriate approach depends on the particular situation. Considering the plan view, it will be sufficient in many scenarios to assume that for a weapon on its side fragments of the cylindrical part of the casing are ejected in two broad sectors, whilst for a weapon standing vertically the fragments are ejected in all directions; in both cases the end cap and base can be taken as travelling along the axis of the weapon.

It is also necessary to consider the angle of elevation. In principle, for the case of an exposed person standing vertically three cases need to be considered, as illustrated in Figure 1. In the near field, shown in Figure 1(a), the fragments hitting the human target are those projected at low angle  $\theta$ ; the fragments approach the target with near normal incidence. In the medium field, shown in Figure 1(b), the target is struck by some fragments of high trajectory issuing at angle  $\alpha \pm \delta_1$  and others of low trajectory issuing at angle  $\beta \pm \delta_2$ ; in both cases the fragments approach the target obliquely. Finally, at the limit of the fragment range, shown in Figure 1(c), these two trajectories combine at an angle  $\gamma$ ; again the fragments approach the target obliquely. This is an idealised model. In practice, due to air drag, fragments slowing

below a critical velocity will tend to stall. In the present work, it is the near field which is of interest and the fragments considered are those with the trajectory shown in Figure 1(a).

The angle of projection is discussed further below, along with ricochet, in relation to stack effects.

### *Retardation of Fragments*

For the retardation of fragments the following equations are used for the velocity as a function of distance. For the supersonic regime use is made of the *Textbook* equation

### EQUATION

$$V = V_0 \exp(-s/284m^{1/3}) \quad V > V_s \quad (7)$$

where  $m$  is the mass of the fragment (oz),  $s$  the distance travelled (ft),  $V$  the velocity of the fragment (ft/s) and  $V_0$  its initial velocity (ft/s).

For the subsonic regime the equation of Christopherson<sup>10</sup> is used:

### EQUATION

$$V = V_0 \exp(-0.00137xa/w^{1/3}) \quad V < V_s \quad (8)$$

with

### EQUATION

$$a = A_m/Q^{2/3} \quad (9)$$

where  $a$  is the dimensionless coefficient of area,  $A_m$  the mean area presented by the fragment in flight ( $\text{ft}^2$ ),  $Q$  the fragment volume ( $\text{ft}^3$ ),  $V_s$  the velocity of sound (ft/s) and  $w$  the mass of the fragment (oz). The value quoted for the velocity of sound is 1100 ft/s.

### *Probability of a Hit*

The *Textbook* gives a set of equations, derived from first principles, which give the probability that a person exposed will be hit by any given number of fragments, and these equations are used here.

The fragments actually considered in the *Textbook* are incapacitating fragments, where the capability for incapacitation is defined in terms of a kinetic energy criterion. In the present work, the *Textbook* equations are applied to consider all the fragments. The injury from these fragments is then assessed separately.

Following the approach given in the *Textbook*, the number  $n$  of incapacitating fragments is

#### EQUATION

$$n(x) = \int_0^{\infty} q(v,x) r(x) dv \quad (10)$$

where  $n$  is the number of incapacitating fragments,  $q$  the number of fragments of equivalent velocity  $v$  at distance  $x$  and  $r$  the proportion of fragments of equivalent velocity  $v$  at distance  $x$ .

The density of incapacitating fragments over the area of a sphere, or hemisphere, centred on the exploding object is

#### EQUATION

$$\frac{N(x)}{A_p} = \frac{n(x)}{4\pi x^2} \quad (11)$$

where  $A_p$  is the projected area of the exposed person ( $\text{ft}^2$ ) and  $N$  the average number of incapacitating fragments at distance  $x$ .

Hence

#### EQUATION

$$N(x) = \frac{n(x)A_p}{4\pi x^2} \quad (12)$$

The value of the projected area  $A_p$  is not apparently given explicitly in the *Textbook*, but a value of  $2.8 \text{ ft}^2$  has been inferred.

The probability  $P(H)_r$  that, given this average number, a target is hit by a particular number  $r$  of fragments is given by the Poisson distribution:

### EQUATION

$$P(H)_r = \frac{N(x)^r}{r!} \exp(-N(x)) \quad (13)$$

The probability  $p$  of being hit by one or more incapacitating fragments is

$$p = 1 - \exp(-N(x))$$

### Injury by Fragments

At the turn of the last century the German army adopted a projectile kinetic energy of 78 J (58 ft lb) as incapacitating to military personnel. This is also the value which has traditionally been used in Britain and the USA.

A model for injury has been derived, which is based partly on data derived from experiments and partly on data from wounds sustained during the two World Wars. In the present work this hybrid model is the preferred method for estimating the injury effect of fragments, although the 78 J criterion may still be used within the model, if desired.

The injury model is now described.

#### *Classification of injury*

The injury classification used is

- K Injury which is fatal, either immediately or in hospital
- S Injury which is serious, involving perforation of the skin, and which necessitates medical attention, implying hospitalisation
- M Injury which is generally not serious, involving perforation of skin, but which deserves medical attention
- T Injury which is trivial, possibly penetrating the skin but not perforating it, or no injury at all

A serious injury is defined more specifically as one involving the following:

Head and neck	Perforation of the skull
Thorax	Penetration of the 'vulnerable area'
Abdomen	Penetration of the 'vulnerable area'
Limbs	Penetration of the 'vulnerable area'

The abdomen is taken here to mean the abdomen proper and that part of the thorax which is not protected by bone, whilst the thorax is taken as that part of the chest which is so protected.

### *Probability of Injury*

The following probabilities are defined:

P(H)	Probability of hit by fragment
P(H <sub>i</sub> )	Probability of hit by fragment in body region i
P(K)	Probability of fatal injury
P(K <sub>i</sub> )	Probability of fatal injury in body region i
P(S)	Probability of serious injury
P(S <sub>i</sub> )	Probability of serious injury in body region i
P(P <sub>vul,i</sub> )	Probability of penetration of vulnerable area of body region i, equal to probability of fatal or serious injury in that region
P(P <sub>skin</sub> )	Probability of perforation of skin
P(P <sub>skull</sub> )	Probability of perforation of skull
P(P <sub>thor</sub> )	Probability of penetration of vulnerable area of thorax
P(P <sub>abd</sub> )	Probability of penetration of vulnerable area of abdomen
P(P <sub>limb</sub> )	Probability of penetration of vulnerable area of limb

Use is also made of the subscripts  $l_{limb}$  and  $u_{limb}$  to denote lower and upper limbs, respectively. The last four probabilities are conditional probabilities, as defined below.

It is assumed that if the body is hit at all by a fragment, the effect is classified using one of the four categories. The trivial injury category covers the cases where the injury is trivial or where no injury is sustained, so that the sum of the probabilities of injury in these four categories is always unity.

Given that the body is struck by a fragment, the probability of the hit occurring in body region i is

$$P(H_i) = A_i/A \quad (15)$$

where A is the total mean projected area (MPA) of the body and A<sub>i</sub> the MPA attributable to that region.

The probability of perforation of the skin is a function of fragment mass, projected area and velocity. It is assumed that perforation of the skin by a fragment will result in either fatality, serious injury, or medium injury (K, S or M).

The probability of penetration to a vulnerable area in body region i is

$$P(P_{vul,i}) = P(P_{vul,i} | P_{skin}) P(P_{skin}) \quad (16)$$

Specifically,for each region considered

	Body region i	
$P(P_{vul,i}   P_{skin}) = P(P_{skull})$	head and neck	(17)
$= P(P_{thor})$	thorax	(18)
$= P(P_{abd})$	abdomen	(19)
$= P(P_{limb})$	limb	(20)

Then for the head and neck

$$P(P_{vul,i}) = P(P_{skull}) P(P_{skin}) \quad (21)$$

for the thorax

$$P(P_{vul,i}) = P(P_{thor}) P(P_{skin}) \quad (22)$$

for the abdomen

$$P(P_{vul,i}) = P(P_{abd}) P(P_{skin}) \quad (23)$$

and for the limbs

$$P(P_{vul,i}) = P(P_{limb})P(P_{skin}) \quad (24)$$

In this model,the probability of fatal or serious injury (K or S) in body region i is defined by  $P(P_{vul,i})$ . The probability of fatal injury is

$$P(K_i) = P(K_i | P_{vul,i})P_{(vul,i)} \quad (25)$$

The probability of serious injury in body region i is then

$$P(S_i) = P(P_{vul,i}) - P(K_i) \quad (26)$$

The overall probability of fatal injury is

### EQUATION

$$P(K) = \sum P(K_i) \quad (27)$$

and that of serious injury is

### EQUATION

$$P(S) = \sum P(S_i) \quad (28)$$

The overall probability of trivial or no injury is

$$P(T) = 1 - P(P_{skin}) \quad (29)$$

and that of medium injury is simply the residue

$$P(M) = 1 - [P(K) + P(S) + P(T)] \quad (30)$$

The probabilities which need to be estimated for this model are therefore for the perforation of the skin

$$P(P_{skin})$$

and the following probabilities for each body region i

$$P(P_{vul,i} | P_{skin})$$
$$P(K | P_{vul,i})$$

*Causative Factor*

Traditionally the criterion for military incapacitation has been expressed in terms of a kinetic energy. Later it became recognised that the presented area of the fragment was also relevant. It has become usual to work, therefore, in terms of the following causative factor X

$$X = mu^2/A \quad (31)$$

where A is the projected area of the fragment (m<sup>2</sup>), m its mass (kg), u its velocity (m/s) and X the causative factor (J/m<sup>2</sup>). This causative factor is effectively the wounding power of the fragment.

### *Perforation of Skin*

A distinction is made between skin penetration, or epidermis perforation, and skin perforation, or full-depth perforation.

For the perforation of bare skin, use is made of a modified version of the correlation of Lewis et al.<sup>11</sup>. This modification is cast in the form of a probit equation:

$$Y(P_{\text{skin}}) = -17.0 + 1.54 \ln(\mu^2/A) \quad (32)$$

It is assumed that on perforation of the skin, there is a reduction in the causative factor ( $\mu^2/A$ ) of 360,000 J/m<sup>2</sup>, the threshold value for skin perforation. The residual energy is then available for further penetration of the body region in question.

### *Penetration to Vulnerable Area: Head and Neck*

For penetration of the head and neck, data from experiments to determine the resistance of the skull to perforation by fragments, given in the *Textbook*, have been used to derive the probit equation:

$$Y(P_{\text{skull}}) = -40.5 + 3.03 \ln(\mu^2/A) \quad (33)$$

### *Penetration to Vulnerable Area: Thorax*

For penetration of the thorax, use has again been made of data given in the *Textbook* for sternum perforation to derive the probit equation:

$$Y(P_{\text{thor}}) = -7.37 + 0.948 \ln(\mu^2/A) \quad (34)$$

### *Penetration to Vulnerable Area: Other Parts*

For other parts of the body use is made of point values for the probabilities of injury given skin perforation. The values are derived from data given in the *Textbook* on British civilian air raid casualties in World War 2 and on British military casualties in World War 1.

### *Effect of Clothing*

The model is intended to apply to persons wearing everyday clothing. Protection afforded by light clothing is assumed negligible since such clothing is much less resistant to perforation than skin.

### *Effect of Advances in Medicine*

Some account is taken in the model of advances in medicine by reducing by half, compared with the World War 2 value, the probability of fatality given penetration to a vulnerable part of a limb  $P(K/P_{\text{vul,limb}})$ .

### *Summary of Injury Model*

The model of injury by fragments may be summarised as follows:

Adjusted values of proportion of MPA assigned to body region i

Body region i	$A_i/A$
Head and neck	0.12
Thorax	0.11
Abdomen	0.16
Upper limb	0.22
Lower limb	0.39

$P(P_{\text{skin}})$  Equation (32) for bare skin

Following skin perforation,  $X$  is reduced by 360,000 J/m<sup>2</sup> to account for the energy expended

$P(P_{\text{skull}})$  Equation (33)

$P(P_{\text{thor}})$  Equation (34)

$P(P_{\text{abd}})$  = 0.84

$P(P_{\text{vul,lwlimb}} | P_{\text{skin}})$  = 0.467

$P(P_{\text{vul,uplimb}} | P_{\text{skin}})$  = 0.467

$P(K | P_{\text{skull}})$  = 0.8

$P(K | P_{\text{thor}})$  = 0.75

$P(K | P_{\text{abd}})$  = 0.75

$P(K | P_{\text{vul,uplimb}})$  = 0.15

$P(K | P_{\text{vul,lwlimb}})$  = 0.345

These last two values incorporate the allowances made for advances in medicine since World

War 2.

### **Application of Model for Single Weapon**

The model is applied as follows. Equation (1) is fitted to the FMD for the particular weapon. The initial velocity of the fragments is calculated using equation (3). A uniform distribution of the projection angles is assumed. The retardation of the fragments is obtained from equations (7) and (8). The probability of defined degrees of injury by fragments is given by the injury model just described. Then at each range the number and spatial density of injuring fragments and the probability of each defined degree of injury are obtained from equations (10)-(14) and the injury model.

### **Explosion of a Stack of Weapons**

So far, the model has been described in terms of its application to situations involving single weapons. In most cases the scenarios of interest will include those for stacks of weapons.

Stack effects may be expected to apply to the number of fragments, the fragment mass distribution, the initial velocity of the fragments and their angle of projection. Since weapons may assume an infinity of different configurations, the problem of predicting stack effects is a complex one. The literature on primary fragments deals almost exclusively with single weapons.

There is available some information on explosions of stacks of munitions, such as that of Draper and Watson<sup>12</sup>, but analysis of this work has not yielded usable correlations for the stack effects mentioned.

In the present work, the authors have assumed that there is no stack effect either on the fragment mass distribution or on the initial velocity of the fragments, although there is certainly some effect on the latter due to 'jetting' effects.

Allowance is made, however, for the number of fragments and a treatment, described below, is given for the effect on angle of projection.

Given this alternative front end, the rest of the model is the same as that for a single weapon.

#### *Projection Angle*

The approach taken to determine the projection angle of fragments from a stack of weapons is as follows. In general, munitions are stacked horizontally on pallets and loaded onto trucks. The effects will therefore be directional, depending on the orientation of the stack relative to the target. The approach adopted is to treat the volume in which there exists a fragment hazard, or hazard volume, as consisting of three zones. These zones are shown in plan view in Figure 2.

In this treatment, the nose and base fragments are emitted in the direction of the axes of the weapons. This results in a narrow zone where there are a small number of large and very hazardous fragments. The side wall fragments are emitted in a rather wider zone normal to the weapon axes. These fragments tend to be smaller but occur in much greater numbers so that a person in this zone is more likely to be hit but to suffer injuries which are not so severe. There is an intermediate zone between these two where hardly any fragments are emitted so that a person situated in this zone is unlikely to be hit. These three zones are termed the end zone, the sidewall zone and the intermediate zone.

In the simplest case, only the sidewall zone is considered. A value is selected of the fraction  $\phi_{szf}$  of the entire hemispherical hazard volume occupied by the sidewall fragment zone. The value currently used is 0.333, which corresponds to emission over a sector of  $60^\circ$  out of a possible  $180^\circ$ .

This parameter  $\phi_{szf}$  may also be adjusted to allow for any enhancement of the spatial density of fragments with a trajectory nearly parallel to the ground, which may occur due to two effects. One is any variation with angle of elevation in the spatial density of fragments leaving the source. The other is any ricochet of fragments from the ground.

Thus for the situation considered, that of a load of weapons lying on their side, an adjustment of 0.75 is currently applied to the factor  $\phi_{szf}$  to allow for both these effects, yielding an overall value of  $\phi_{szf}$  of 0.25 ( $=0.75 \times 0.333$ ). In other words, for this case, the overall spatial density of fragments in the sidewall fragment zone at ground level is four times that which would be obtained assuming a uniform density over the entire hemisphere.

If the ordered stack has been replaced by a jumbled pile of weapons, the fragments are taken as being emitted uniformly over the whole surface of the hemisphere. The unadjusted value of  $\phi_{szf}$  is taken as unity (instead of 0.333), but the same adjustment factor of 0.75 is still applied for the combined effects of angle of elevation and ricochet to yield an overall value of  $\phi_{szf}$  of 0.75.

### **Computer Program EXFRAG**

The program EXFRAG predicts the probability that a human target suffers a defined level of injury from penetrating primary sidewall fragments emitted from the explosion of a stack of cased explosives, or munitions. The probability is conditioned on the person being in direct line of sight of the explosion and so makes no separate allowance for the protection afforded by hard cover.

For any given distance it calculates the average number of fragments expected to hit the target; the probability of any given number striking it; the velocity and wounding power of each fragment; the probability that the target suffers a defined level of injury from that fragment; and the probability that the target suffers a defined level of injury from the whole set of fragments.

In the program the effective area of the target is projected back to the explosion centre, so that only those fragments need be considered which will hit the target. The probabilities that the target is hit by one, two, three, etc., fragments is obtained from the Poisson distribution. Monte Carlo simulation is then used to determine the number and size distribution of these fragments.

## **Numerical Results**

The fragment injury model has been tested by running the program EXFRAG for the cases of a single weapon and for a stack of weapons.

Table 1 shows the format of the input data to the program, for the case of a stack comprising a single unit of 4 x 105 mm shells.

The program has been run to simulate the effect of the explosion of the explosive object on a person standing at distances between 5 and 500 m. Tables 2 and 3 show the results for a single unit consisting of 4 x 105 mm shells. Table 2 gives the density of injurious fragments, these being defined as fragments which have a kinetic energy of at least 80 J (58 ft lb).

Table 3 gives the probabilities of injury. There are several features of the table which are noteworthy. First, for every category the probability of injury falls off sharply with distance. Second, the determining factor in this fall-off is essentially the probability of being struck by a fragment in the first place. Third, beyond 100 m the probabilities of injury become extremely low, but the probability of being struck does not drop off as rapidly. This would seem to indicate that beyond this range very few fragments have the energy to cause more than a trivial injury.

The effect of the explosion of a set of stacks containing from 1 to 1000 units of 4 x 105 mm shells has also been simulated. The assumption was made that there is no stack effect so that the total number of fragments generated is proportional to the number of weapons and there are no effects such as interference. To the extent that interference does occur, these results are conservative. Table 4 shows the results for the set of stacks.

## **Discussion**

A model for the injuries to be expected from impact by primary fragments generated by an explosion of munitions has been derived. It may be used to determine the probability of injury as a function of distance for this particular mode of injury and is incorporated within the overall explosion effects consequence model.

A feature of the model is a new method of estimating the probability of defined degrees of injury to a person hit by fragments of given mass, mean projected area and impact velocity.

The model may be applied to the explosion of a stack of weapons. However, there are some

attendant uncertainties in doing this. In order to apply the model to a stack it is necessary to know the number of fragments, the fragment mass distribution, the initial velocity and the angle of projection. The approach taken is to assume that information is available on the number of fragments and that the FMD and initial velocities can be taken as unaffected by stack effects and to utilise a model for angle of projection from a stack.

The probability of injury is effectively proportional to the spatial density of the fragments, which is affected by the launch angle and ricochet effect. The model results are therefore sensitive to the configuration of the stack and to the value adopted for the factor  $\phi_{szf}$ .

A computer program EXFRAG has been written to implement the model.

Results have been obtained for a single unit of 4 x 105 mm shell and are shown in Table 3. These results show that for every category of injury the probability falls off rapidly with distance. In the near and medium fields, the probability of injury is governed by the probability of being hit. In the near field, the degree of injury depends largely on the part of the body which is struck, whilst in the medium field the injuring power of the fragments becomes increasingly significant. In the far field, the probability of being hit decays gradually, but the probability of injury falls off rapidly as the fragments lose their injuring power.

Another approach to handling stack effects is the use of the computer code FRAGHAZ<sup>13</sup>. This program simulates generation and flight of fragments from an exploding stack. FRAGHAZ has the potential to act as the front end of the present model.

A fuller description of the model is given in references 6-8 of the companion paper<sup>1</sup>.

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**Table 1 Input data for simulation of a test case involving a single unit of 4 x 105 mm shells, filled with TNT**

	Numerical value	Units
<b>A Explosive</b>		
No. of atoms of C per mole of explosive <sup>(a)</sup>	7	-
No. of atoms of H per mole of explosive	5	-
No. of atoms of N per mole of explosive	3	-
No. of atoms of O per mole of explosive	6	-
Internal energy of formation of explosive	-185	kJ/kg
Initial loading density of explosive	1.63	g/cm <sup>3</sup>
<b>B Weapon</b>		
Density of metal casing <sup>(b)</sup>	7.75	g/cm <sup>3</sup>
Case/charge weight ratio	0.5	-
Number of fragments per unit	250	-
Held's FMD parameter $B_B$ for single unit	0.0291	User <sup>(c)</sup>
Held's FMD parameter $\lambda_B$ for single unit	0.900	User
Held's FMD parameter $M_{OB}$ for single unit	35000	User
Conversion factor FMD unit to gram	0.0648	User
Mean projected area parameters:		
Coefficient (slope)	0.7 cm <sup>2</sup> /g <sup>2/3</sup>	
Intercept	0	
Standard deviation	0	
<b>C Stack</b>		
Number of units in stack	1	-
Effective stack radius <sup>(d)</sup>	0.1	m
Effective depth of zone through which fragments have to travel before overtaking the shock front	0.4	m
Fraction of hemispherical hazard volume occupied by sidewall fragments	1	-
<b>D Target</b>		
Distance of target from centre of stack	Variable	m
Presented area of target	0.557	m <sup>2</sup>
(a) These values are for a TNT filling		
(b) These values are for 105 mm shell		
(c) FMDs tend to be given in a variety of units. The appropriate conversion factor is therefore entered by the user		
(d) Distance to outer surface of stack		

**Table 1 Input data for simulation of a test case involving a single unit of 4 x 105 mm shells, filled with TNT**

**Table 2 Density of injurious fragments vs distance predicted by fragment injury model for explosion of a single unit of 4 x 105 mm shells**

Distance (m)	No. of injurious fragments	Area over which injurious fragments are distributed (m <sup>2</sup> )	No. of injurious fragments/600 ft <sup>2</sup>
2	1165	25	2600
5	911	157	320
10	790	628	70
20	647	2,510	14
50	443	15,700	1.6
75	379	35,300	0.6
100	310	62,800	0.28
150	229	141,000	0.09
200	192	251,000	0.04
500	46	1,570,000	0.0016

(a) An injurious fragment is taken as one having a kinetic energy of at least 80 J (58 ft lb)

**Table 2 Density of injurious fragments vs distance predicted by fragment injury model for explosion of a single unit of 4 x 105 mm shells**

**Table 3 Probabilities of injury vs distance predicted by fragment injury model for explosion of a single unit of 4 x 105 mm shells**

Distance (m)	Probability of injury (%)				
	P(K)	P(S)	P(M)	P(T)	P(H)
5	24.5	19.2	15.1	41.2	66.7
10	6.70	6.68	6.51	80.1	21.8
20	1.72	1.81	1.86	94.6	5.7
50	0.24	0.26	0.29	99.2	0.90
75	0.08	0.09	0.10	99.7	0.40
100	0.03	0.04	0.05	99.9	0.22
150	0.01	0.01	0.01	≈100	0.10

(a) The number of fragments per unit was taken as 250

(b) P(H) is the probability that the body is struck by one or more fragments

**Table 3 Probabilities of injury vs distance predicted by fragment injury model for explosion of a single unit of 4 x 105 mm shells**

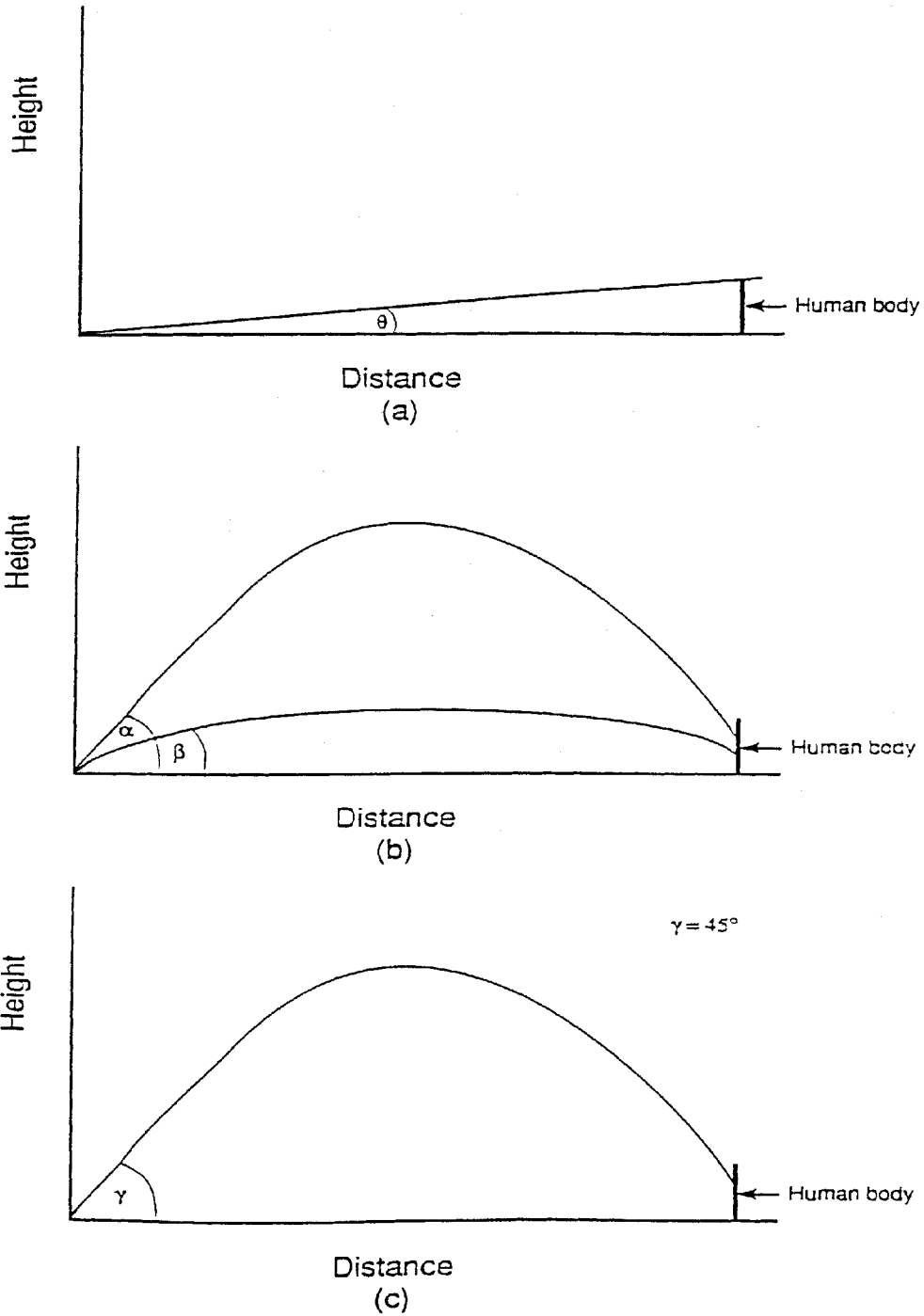
**Table 4 Probabilities of injury at 100 m distance predicted by fragment injury model for explosion of stacks containing various numbers of units of 4 x 105 mm shell**

No. of units	Probability of injury (%)			
	P(K)	P(S)	P(M)	P(T)
1	0.03	0.04	0.05	99.9
2	0.07	0.08	0.09	99.8
5	0.17	0.20	0.23	99.4
10	0.34	0.39	0.46	98.8
100	3.32	3.68	4.15	88.9
1000	29.6	20.6	17.1	32.7

(a) The number of fragments per unit was taken as 250

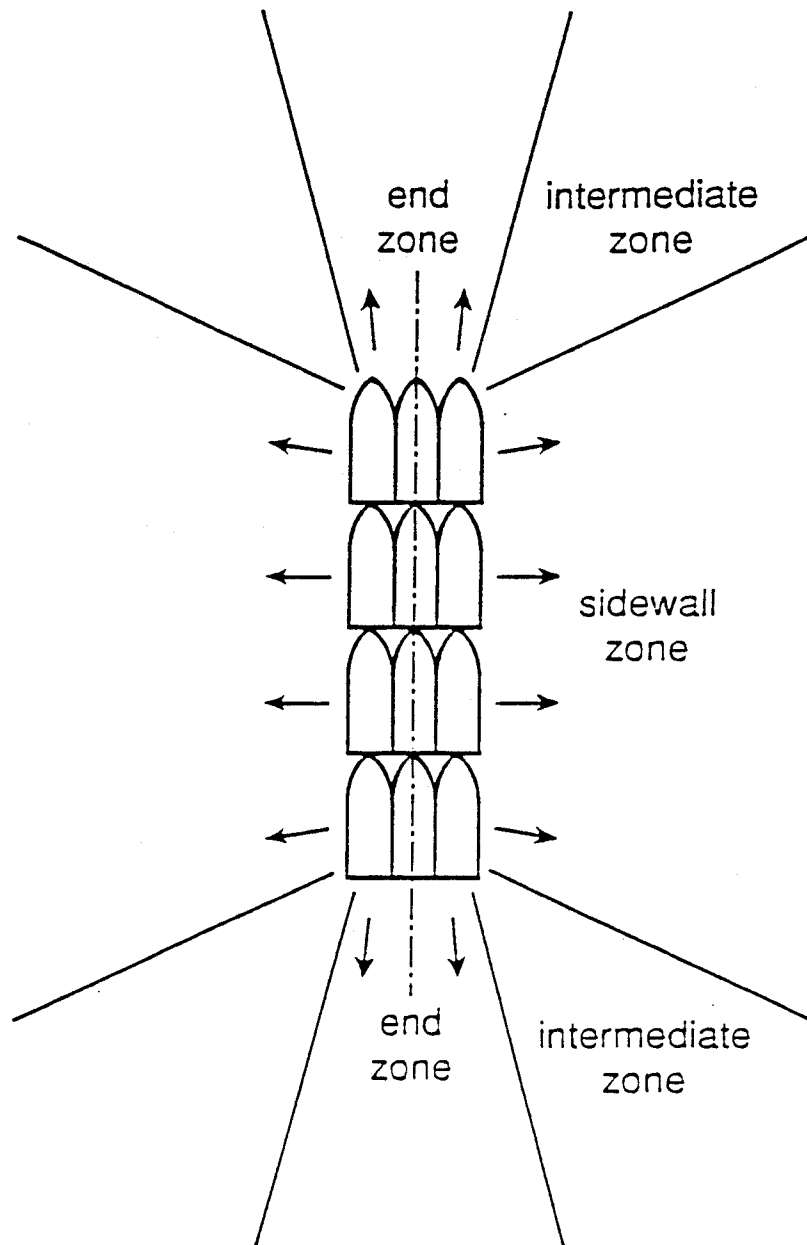
**Table 4 Probabilities of injury at 100 m distance predicted by fragment injury model for explosion of stacks containing various numbers of units of 4 x 105 mm shell**

**Figure 1 Angle of projection of casing fragments: (a) near field; (b) medium field; and (c) limit of range**



**Figure 1 Angle of projection of casing fragments: (a) near field; (b) medium field; and (c) limit of range**

**Figure 2**  
**Plan view of zones of projection of fragments from a stack of weapons**



**Figure 2** Plan view of zones of projection of fragments from a stack of weapons