

A Model for Hazard Assessment of the Explosion of an Explosives Vehicle in a Built-Up Area

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A model is described for the hazard assessment of the accidental initiation of condensed phase explosives during transit in a built-up area. The model is in two parts. The first part is a scenario model which allows the user to configure a specific scenario and the second part is a set of consequence sub-models. These sub-models cover the explosion effects and the injuries to be expected from them. The explosion effects are the blast, fireball, primary fragments (casing), crater ejecta, falling debris, building collapse and flying glass. Each submodel gives the intensity of the physical effects as a function of distance and the probability of injury as a function of that intensity. Illustrative examples are given of the injuries to be expected from the explosion of explosive loads.

Introduction

In the UK the road transport of explosives, including munitions, is increasingly subject to hazard assessment. This creates the need for a model of the consequences of an explosion of military explosives. A model is described which has been developed to assess the injuries that may be caused by a condensed phase explosion during transport, particularly through built-up areas. The scope of the model is to assess the consequences of such an explosion and it does not extend to the frequency of the event. It is intended for assessing the number of persons injured by an explosion, primarily at a particular location, but also by extension along a route. The main application of the model is to the hazard assessment of the transport of military explosives but it is applicable also to commercial explosives.

The model is described in detail in a set of papers written for the Ministry of Defence¹⁻⁹. One part of it, the model for fragmentation and fragment injury, is described in a companion paper¹⁰.

The account which follows is a simple statement of the model. The detailed justification of the relations used, which is not possible within the constraints of this summary paper, is given in the papers just referenced.

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Effects of Explosion

The principal effects of a condensed phase explosion such as the explosion of a load of cased explosives, or munitions, on a lorry which are relevant here are (1) blast; (2) fireball; (3) missiles (primary, secondary fragments); (4) falling debris; (5) building collapse; and (6) flying glass. The injurious blast wave effects include overpressure and bodily translation. Primary fragments are those generated by the disintegration of the casing of the munitions. Secondary fragments are taken to include fragments from the vehicle and from the crater as well as objects set in motion by the blast wave. Falling debris includes masonry and window glass.

These effects are illustrated in Figure 1.

Peterborough Explosion

In 1989 an explosion occurred of the load of a vehicle carrying commercial explosives in a factory yard at Peterborough in the UK. The load had a TNT equivalent of some 800 kg. Prior to the explosion smoke was seen coming from the vehicle and people were drawn by curiosity. At the time of the explosion there were some 45 persons within a radius of 60 m. The report of the accident investigation by the Health and Safety Executive¹¹ contains much useful information.

Data from this incident have been used in the model as a check on injury, particularly from the fireball and from flying glass.

Outline of Model

The elements of the overall explosion model are as follows:

- (1) Scenario model
- (2) Consequence model
 - (a) Outdoor injury
 - (i) Blast model
 - (ii) Fireball model
 - (iii) Missile models
 - (iv) Falling debris model
 - (b) Indoor injury
 - (i) Housing damage model
 - (ii) Indoor injury model
 - (iii) Flying glass model

The scenario model covers the population density, the populations' disposition indoors and outdoors, the categories of exposure, the incident scenarios and the vulnerabilities of persons in each exposure category in given scenarios.

Outdoor injury is accounted for by sub-models relating particular physical effects to injury in corresponding modes. These cover lung haemorrhage, bodily translation, and eardrum rupture; engulfment by and burns from the fireball; wounds from casing fragments and other missiles; and injury by falling debris.

The blast model is the conventional TNT model which provides the characteristics of a blast wave from a condensed phase explosion. The fireball model is a new model for determining characteristics of the fireball from initiation of a condensed phase explosive. These two physical effect sub-models are used in conjunction with correlations for injury from these effects. The primary fragmentation model is also a new model and predicts the number, size distribution, trajectory and velocity of missiles projected from a cased explosive. It is used in conjunction with a new model for the wounding power of fragments. The falling debris model is a new model relating injury in the vicinity of buildings to severity of housing damage. There is also a submodel for assessing the hazard presented by secondary fragments.

The housing damage model gives the severity of housing damage as a function of the effective mass of the explosive and distance. It is essentially a modification of the well-known Jarrett equation. The indoor injury model is based essentially on the relationship between housing damage and injury.

The relative importance of injury outdoors and indoors depends on the scenario considered. In general, at any given time the great majority of the population is indoors. On the other hand situations of particular interest may involve populations which are mainly outdoors.

The overall model is now described. The account is necessarily a brief one, highlighting principal features. The structure of the model is shown in Figure 2.

Scenario Model

For the type of explosion considered, the elements of a scenario are the events prior to the situation of imminent risk; the human behaviour prior to the explosion; the explosion itself; and the physical characteristics of the location. These provide the location and exposure of persons at risk.

The most common scenario for the realization of the hazard is that of engulfment of the explosive load in a fire which lasts long enough to initiate an explosion. This scenario is important not only by virtue of its relative frequency, but also because all the features just mentioned are relevant, which is not the case for every scenario.

The purpose of the scenario model is to define the population at risk at the instant that the explosion occurs. Categories of persons exposed are defined which are intended to be exhaustive over the whole course of the scenario and estimates are made of the numbers in each category at the start of the scenario and of the change in these numbers with time until the explosion occurs.

A distinction is made between location groups and exposure groups. A location group defines the persons in a particular type of location and an exposure group the persons subject to the particular set

of physical effects for that location. Essentially, the scenario model yields the number of persons in each exposure group in each annulus as a function of time

Consequence Model

Injury Categories

The various models give the probability of sustaining a given degree of injury. The production of an overall model with defined degrees of injury is not straightforward, since the correlations available in the literature for injury in different modes tend to use different injury definitions.

In the work on air raid casualties use has been made of the definitions

K	killed
S1	serious hospital casualty
LI	slight hospital casualty
U	no injury requiring hospital treatment

In the indoor injury model the categories used, derived from the above, are fatal (K), fatal and seriously injured (K+SI) and fatal and hospitalised (K+SI+LI).

Outdoor Injury Model

Blast Model

The correlations used for peak side-on overpressure and positive impulse from a TNT charge at ground level (hemispherical symmetry) are those of Kingery and Pannill¹² and Kingery¹³.

For a target situated well away from a reflecting surface, the peak effective overpressure is equal to the peak side-on overpressure, i.e. $p_e^0 = p^0$ but in a built environment a proportion of targets are situated near a reflecting surface, and the value of p_e^0 is enhanced. Following the approach taken by Reed¹⁴ in respect of the effective overpressure on windows, the enhancement factor is taken on average, over all configurations and orientations, as 1.32 so that

$$p_e^0 = 1.32 p^0$$

This relation is used to characterise overpressure experienced in close proximity to buildings.

Blast Injury Model

Eardrum rupture

For eardrum rupture use has been made of the relation given by Hirsch¹⁵, which may be represented by the probit equation

$$Y = -12.6 + 1.524 \ln p_e^0 \quad (2)$$

where p_e^0 is the peak effective overpressure (Pa) and Y the probit.

Lung injury

For lung injury use is made of the plot given by Baker et al.¹⁶ which indicates that for injury to man at atmospheric pressure from charges of TNT equivalent >10 kg, injury depends almost entirely on overpressure. The relevant part of the diagram can be simplified for fatal injury to the following probit equation:

$$Y = -32 + 6.751 \ln p_e^0 \quad (3)$$

where p_e^0 is the peak effective overpressure (kPa).

Bodily translation

The treatment of injury by whole body displacement is potentially complex. A fundamental treatment for a standing person involves consideration of the following effects: (1) displacement from the upright to the prone posture, (2) bodily translation followed by impact of the skull, (3) bodily translation followed by impact of the whole body, and (4) tumbling across open terrain, or decelerative tumbling. In the first three cases injury is due mainly to a single impact with a non-yielding surface, whilst in the fourth flailing of the limbs is a significant contributor.

In the model the approach taken is to estimate the maximum velocity attained by the body and to use this value in correlations for injury by bodily translation.

For the velocity of the body, the force acting on the body initially is

$$F = C_D q^0 A \quad (4)$$

where A is the projected area of the body (m^2), C_D the drag coefficient, F the force acting on the body (N) and q^0 the peak dynamic pressure (Pa). For the drag coefficient of the human body the value used by Baker et al.¹⁶ for C_D is 1.3. The dynamic pressure decays from the peak dynamic pressure to zero over the period of the dynamic pressure duration t_q . Assuming that the shape of the dynamic impulse i_q can be approximated by a triangle

EQUATION

$$i_q = \frac{1}{2} q^0 t_q \quad (5)$$

where i_q is the dynamic pressure impulse (Pa.s) and t the dynamic pressure duration (s).

Neglecting deceleration, the velocity V attained by a body of mass m due to this impulse is given by

EQUATION

$$mV = \frac{Ft_q}{2} \quad (6)$$

where m is the mass of the body (kg) and V the velocity imparted to the body (m/s).

The relation for the peak dynamic pressure has been given above. For dynamic pressure impulse use is made of the following relation given by Richmond and Fletcher¹⁷:

EQUATION

$$\ln R = \frac{5.4054 + 1.1067 \ln W - \ln i_q}{2.3201} \quad (7)$$

where i is the dynamic pressure impulse (psi.ms), R the distance (ft) and W the mass of explosive (lb) (as TNT equivalent). These equations allow the maximum velocity imparted to the body to be estimated.

The velocity V so calculated is a maximum value, before any retardation, and its use in injury relations is therefore somewhat conservative.

For injury due to translation of the body, the correlations used are the probit equation for fatal injury of Jones, Richmond and Fletcher¹⁸:

$$Y = -2.14 + 2.54 \ln V \quad (8)$$

and that for serious injury of Fletcher et al.¹⁹:

$$\ln R = \frac{5.4054 + 1.1067 \ln W - \ln i_q}{2.3201} \quad (7)$$

$$Y = 0.82 + 2.697 \ln V \quad (9)$$

In principle, separate treatment is appropriate for injury by decelerative tumbling on the open, but for the built-up environment which is of prime interest this mode is assumed to be less significant than those just described.

Fireball Model

The fireball model is a new model. There are numerous correlations for the fireballs of hydrocarbons, but relatively little for those of solid explosives or liquid propellants. In the case of commercial (uncased) explosives particularly, the fireball is a significant contributor to the hazard, as evidenced at Peterborough.

The growth of the fireball is assumed to occur in three stages as shown in Figure 3. In Stage 1 the explosive undergoes the detonation reaction and forms the detonation products. In Stages 2 and 3 air is entrained into the cloud formed by these initial products. If the combustion is not substantially complete in Stage 1, the reaction of the detonation products with the entrained air gives an 'afterburn'. Stage 2 ends with the fireball, at its maximum hemispherical size just about to lift off. Stage 3 lasts until the end of the fireball, usually taken as the point at which the flame is no longer visible.

The model gives the maximum diameter attained by the fireball and the temperatures at the end of Stages 1 and 2. The combustion in Stage 1 is assumed to be adiabatic. A separate heat loss model is used to determine the heat loss over the duration time of the fireball, and hence the profiles of the radius, the temperature and the heat flux with time.

The base case is taken as a fireball of TNT. This explosive is deficient in oxygen and therefore requires addition of air to complete combustion. The basic assumption of the model is that the quantity of air mixed into the fireball by the end of Stage 2 is based on the stoichiometric amount associated with the appropriate reaction scheme.

The diameter of the fireball may be obtained directly from the volume of the combustion products so computed. The duration time is more difficult, but an estimate has been made from the rather sparse information on duration of fireballs formed from high explosives. The empirical relations obtained for the diameter and duration of the TNT fireball are

$$D = 35M^{0.333} \quad (10)$$

$$t_d = 0.3 M^{0.333} \quad (11)$$

Equation (10) gives for the diameter of the fireball at Peterborough a value of 32 m, which compares with the estimate of 36 m made in the HSE report.

For the profile of the shape and temperature the approach taken is as follows. The time required for the fireball to reach its maximum diameter is a small fraction of the total duration time. Even the time required to reach its maximum height is much less than the duration time. It is convenient to define a time t_s , which is the time at which the shape of the fireball changes from the maximum diameter hemisphere to a sphere, still at ground level:

EQUATION

$$t_s = \phi t_d \quad (12)$$

From information on the fireballs of solid explosive the estimate made for ϕ is 0.25.

The heat radiation from the fireball is given by the equation

EQUATION

$$q = \sigma \epsilon T^4 \quad (13)$$

where q is the radiant heat flux (kW/m^2), ϵ the emissivity of the fireball and σ the Stefan-Boltzmann constant ($\text{kW/m}^2 \text{K}^4$).

The rate at which heat is radiated from the fireball is then

$$Q = qA \quad (14)$$

where A is the surface area of the fireball (m^2) and Q the rate of heat radiation (kW).

The shape of the fireball is taken as a hemisphere up to time t_s and thereafter as a sphere. This gives the area for heat radiation over the duration of the fireball.

As a first approximation, the emissivity of the fireball may be taken as unity.

The extinction of the fireball is taken as occurring when it ceases to be visible, at about 1150 K.

The profile of the temperature of and heat radiation from the fireball of a TNT explosion as a function of time as predicted by the model is given in Table 1.

As indicated in the table, the radiant heat flux and temperature at a given fraction of the duration time are the same for all masses of explosive. The justification for this is as follows. The heat generation is proportional to the mass M of the fireball, the heat loss per unit time is proportional to the surface area A , the heat loss at a given fraction of the duration time is proportional to the product At_d , the surface area

A is proportional to $M^{2/3}$ and the duration time t_d is proportional to $M^{1/3}$.

Further temperature profiles for four different explosives are given in Figure 4. Since in the

model the temperature profile is independent of the charge size, Figure 4 gives for each particular explosive a universal profile which may be used to calculate the heat radiated as a function of time.

The correlation in Figure 4 is in terms of the duration time for a TNT fireball. For fireballs of other explosives, an effective duration may be obtained from the graph using a suitable value of the termination temperature T_f . As just stated this is taken here as 1150 K.

Summarising, the fireball model consists essentially of equations (10)-(14) and the universal temperature profiles given in Figure 3 together with the values given for the fraction ϕ of the duration over which the afterburn occurs and the final temperature T_f .

The heat received by the target is given by

EQUATION

$$\tau = \exp(-kL) \quad (16)$$

where F is the configuration, or view, factor, I the heat received by the target (kW/m^2), L the distance between the surfaces of the fireball and the target (m), α the absorptivity of the target, τ the transmissivity of the air and k a constant (m^{-1}).

with

EQUATION

$$I = q F \alpha \tau$$

In the present case, where the fireball will be such as to cause injury only at relatively short distances, it is sufficient to take $k=0$. Further it is common practice to take $\alpha=1$.

Expressions for the view factor between a sphere and a differential target are given in the literature. For a fireball which is a sphere of radius R just touching the ground radiating to a target standing perpendicular to the ground at a distance x from the point at which the fireball is in contact with the ground the view factor is

EQUATION

$$F = \frac{R^2 x}{(R^2 + x^2)^{3/2}} \quad (17)$$

where R is the radius of the fireball (m) and x the distance between the fireball and the target (m). At large distances equation (44) reduces to

$$F=(R/x)^2 \quad (18)$$

Fireball Injury Model

The fireball may cause injury by flame engulfment or by transmission of thermal radiation. In the first case, it is assumed, perhaps conservatively, that engulfment is fatal. For fatal injury due to transmitted thermal radiation use is made of the probit equation given by Hymes²⁰, following Eisenberg, Lynch and Breeding²¹:

$$Y = -14.9 + 2.56 \ln (tI^{4/3}/10^4) \quad (19)$$

where I is the thermal flux (W/m²), t time (s) and Y the probit.

Primary Fragments and Fragment Injury Model

This model gives the number, mass distribution, initial velocity, projection angle and retardation of fragments from a cased explosive and the probabilities of defined degrees of injury from such fragments. An account of the model is given in the companion paper¹⁰ and it is therefore not described further here.

Crater Ejecta and Ejecta Injury Model

Crater ejecta may also cause injury and a model is included for crater ejecta and injury by such ejecta. In the present work use has been made of the work of Henny and Carlson²² as described by Richmond and Fletcher¹⁷.

By comparison with the primary fragments from casing, the ejecta are less numerous but larger. Cases studied suggest that the absolute contribution of crater ejecta to fatal injury is small relative to that of primary fragments and that the relative contribution does not change greatly with distance.

Falling Debris Injury Model

A person in the street near to a building is vulnerable to falling masonry and glass. The extent of the hazard from these two sources will vary. The relative importance of falling glass may be expected to increase where the buildings in question are large city skyscrapers. The point is illustrated by the large falls of window glass caused by recent terrorist bombs in the City of London.

The model used relates the probability of sustaining a given degree of injury to the category of housing damage, defined below, and is

Housing damage category	Probability of injury (%)	
	Killed	Seriously injured
Ab	90	100
Aa	50	75
B	1	25
Cb	0	1

The housing damage categories are discussed below. The injury values are arbitrary but are considered reasonable.

Housing Damage Model

Categories of housing damage

The housing damage categories used are those given by Jarrett²³:

- A almost complete demolition
- B 50-75% external brickwork destroyed or rendered unsafe and requiring demolition
- Cb houses uninhabitable - partial or total collapse of roof,partial demolition of one to two external walls,severe damage to load-bearing partitions requiring replacement
- Ca not exceeding minor structural damage,and partitions and joining wrenched from fittings
- D remaining inhabitable after repair - some damage to ceilings and tiling,more than 10% window panes broken

One modification has been made to this: the A category is subdivided into two subcategoriesA_b and A_a,with the former the more severe,as in the C category. For A_b housing damage fatal injury of the occupants is almost certain.

Housing damage correlation

The housing damage model is a revision of the well-known Jarrett equation,relating the category of housing damage to the mass of explosive. The revision is based on a detailed study of damage done by Oerman weapons during World War 2 in Britain,mainly London. The study has involved the examination of the original wartime reports,including those on which Jarrett based his paper; estimation of the effective bare charge weight of the individual weapons; and survey of the housing damage done by the individual weapons.

The equation is

EQUATION

$$R = \frac{kW^{1/3}}{(1 + (3175/W)^2)^{1/6}} \quad (20)$$

where R is the distance (m) and W the mass of explosive (kg). The mass of explosive is the TNT bare charge equivalent. The values of the constant k are given below.

For category B damage the value of k is 7.1 and from equation (20) the average circle radius (ACR) for such damage R_B is

EQUATION

$$R_B = \frac{7.1 W^{1/3}}{(1 + (3175/W)^2)^{1/6}} \quad (21)$$

A dimensionless quantity RB is defined as the ratio of the distance for a given category of damage to that for B category damage. The constants for use in equation (20) and the corresponding values for RB are

Damage category	Constant k	RB ratio
A	4.8	0.675

$$z' = \frac{R}{W_e} \quad (23)$$

B	7.1	1.00
Cb	12A	1.74
Ca	21.3	3.0
D	42.6	6.0

The value of k for A_b category damage is 2.1.

The results have also been expressed in the form of a pressure-impulse diagram.

Indoor Injury Model

Injury Inside Damaged Housing

The overall model contains three sub-models relating degree of injury to the mass of explosive.

The first model utilises the housing damage equation (20) in combination with data on injury sustained in V-2 rocket incidents. The data are taken from the *Textbook of Air Armaments of the Ministry of Supply*²⁴. Table 2 gives data on injuries in 12 V-2 incidents. Using equation (20), these data have been converted to a relationship between the housing damage category and the degree of the injury. This is shown in Table 3.

Both the second and third models are based on the same data, but are cast in alternative forms. The second model expresses injury as a function of the ACR for damage categories.

The third model is cast in the form of a set of probit equations:

$$Y = 6.923 - 1.70 \ln z' \quad \text{K injury} \quad (22a)$$

$$Y = 7.626 - 1.89 \ln z' \quad \text{K+SI injury} \quad (22b)$$

$$Y = 7.955 - 1.77 \ln z' \quad \text{K+SI+LI injury} \quad (22c)$$

with

EQUATION

$$z' = \frac{R}{W_e} \quad (23)$$

and

EQUATION

$$W_e' = \frac{W_e^{1/3}}{\left[1 + \left(\frac{3175}{W_e} \right)^2 \right]^{1/6}} \quad (24)$$

where We' is an effective charge term ($kg^{1/3}$) and z' a modified scaled distance ($m/kg^{1/3}$). This scaled distance is based on equation (21) and relates to the extent of housing damage. It is considered to be a more appropriate causative factor than overpressure.

Injury Inside Other Buildings

In many scenarios the buildings of interest will be buildings other than, or in addition to, housing. In the model this essentially complex problem is dealt with in a relatively simple manner.

The wartime records show, as indicated in Table 4, that the Standardised Casualty Rates (SCRs), or casualty rates standardised for weapons charge, for persons exposed in other buildings were almost identical with those for persons exposed in housing. As a first approximation, therefore, other buildings are treated on a par with housing.

Flying Glass Model

Flying glass is a particular cause of injury for persons exposed indoors near windows. As such, it is essentially subsumed in the indoor injury model. In other words, a separate flying glass injury model is not required in order to estimate the total number of hospitalizing injuries indoors.

However, most of the injuries sustained in the far field are minor cuts due to flying glass and for this reason it is desirable to have a separate model for flying glass injury.

The model developed consists of relations for the likelihood of window breakage and for the velocity of the glass fragments together with a value of the average mass of fragments with significant wounding power. The model assesses whether a person exposed at a window will be hit and thereby cut by at least one such fragment.

For the breaking pressure of windows use is made of the work of Reed¹⁴. He gives a graph for the probability of breakage versus the peak incident overpressure, from which the following probit equation has been derived:

$$Y = -4.77 + 1.091 \ln p_{eq}^0 \quad (25)$$

where p_{eq}^0 is the peak overpressure experienced by the standard pane (Pa) and Y the probit for window breakage.

The window taken as standard by Reed is a single-strength glass 2 ft x 2 ft x 2 mm thick. For other windows the following relation may be used to determine the peak effective overpressure required to effect the same response:

EQUATION

$$p_{eq}^0 = \left(\frac{(A/0.372)}{(t/0.002)} \right) p_e^0 \quad (26)$$

where A is the area of the pane (m^2), p_e^0 the peak effective overpressure (Pa), p_{eq}^0 the equivalent overpressure for use in equation (25) (Pa) and t the thickness of the glass (m).

The peak effective overpressure is obtained from equation (1).

Flying Glass Injury Model

For injury from flying glass use is made of the following probit equations given by Hadjipavlou and Carr-Hill²⁵ for laceration and for penetration, respectively:

$$Y = -12.23 + 0.83 \ln mV^4 \quad \text{laceration} \quad (27)$$

$$Y = -8.35 + 0.61 \ln mV^4 \quad \text{penetration} \quad (28)$$

where m is the mass of the fragment (g) and V its velocity (ft/s). Equation (28) for penetration refers to the penetration of the abdomen in dogs.

Correlations are available for the spatial density of fragments from breaking windows. However, it is the larger fragments which have the significant injuring power. In the model the value for the mass of the significant fragments is taken as 50 g. Some justification for this value is obtained from the following analysis of flying glass injuries at Peterborough.

In this incident the window breakage was recorded as follows:

EQUATION

Distance (m)	Proportion of windows broken (%)
≈225	90
≈360	50
≈580	5

and the injuries from flying glass were

Distance (m)	Peak incident overpressure (psi)	Injury
0-50	>5.5	Cuts to all persons
70-100	3.2-1.9	Cuts to many persons
100-150	1.9-1.15	Cuts to few persons
≈200	0.80	Furthest distance for cuts

Multiple Injury and Double Counting

Allowance is made in the model for multiple injury so as to avoid double counting. The approach taken is mathematical rather than physiological.

Computer Program EXMOD

The program ExMOD predicts the probability that a human target suffers a defined level of injury from each of the explosion effects described above. This probability is a function of the distance from the exploding object and of the type of exposure. The susceptibility of the person is defined at the instant of initiation in terms of the location and exposure groups described earlier, in addition to the distance.

The general approach is to use the physical model to compute the intensity of the physical effect and then the injury model to relate this intensity to the probability of injury.

As described in the companion paper, a computer program BRAG has been developed for injury by primary fragments. ExMOD utilises this program as a sub-program for the determination of the probabilities of injury from such fragments.

Some Results from the Model

Some results from the model, obtained employing the EXMOD program, are given in Table 5 and in Figure 5. Table 5 shows the probabilities of injury versus distance for persons situated

outdoors to the explosion of a single unit of six Mk82 bombs. Section A of the table gives the physical effects and damage, and Sections B and C the probabilities of injury.

Figure 5 shows the number of casualties predicted for the explosion of munitions of different effective charge weights in a built-up area with a uniform population density of 4210 persons/km². The plot is based on the assumption that the load is located randomly and makes no allowance for the fact that in most cases there will be an area of road, and possible gardens, etc., between the explosion and any buildings; this assumption is particularly conservative for small loads.

The results given in Table 5 show that up to about 25 m for persons away from buildings the probability of fatal injury is dominated by primary fragment injury, whilst for persons near buildings the chance of fatality is much increased by falling debris. Beyond this distance the effect of falling debris declines rapidly, leaving primary fragments as the dominant cause of fatal injury.

Discussion

A model has been given for the effects of a condensed phase explosion in a built-up area. The main application of the model is to hazard assessment, primarily to scenarios involving the transport of explosives, cased or uncased.

In the overall model the exposure of human targets is defined in terms of location and exposure groups by the scenario model. The consequence model is in two parts, one for injury outdoors and another for injury indoors. The indoor injury model comprises a relation for housing damage and another for injury given such damage. The outdoor injury model is a set of constituent sub-models, which typically consist of a model for the intensity of the physical effect coupled to an injury relation.

The consequence model is embodied in the computer program EXMOD.

The sub-model for fragmentation of a cased explosive and for fragment injury is embodied in the program EXFRAG, which may be used in the stand-alone mode, or as a sub-program within EXMOD.

Some results from the model have been given. The results appear not unreasonable but the authors would be interested in information which might make it possible to perform crosschecks and further validation.

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Table 1 Fireball temperature and heat flux profile for TNT predicted by heat loss model

Fraction of duration time (s)	Temperature (K) (all masses of explosive)	Heat flux (kW/m ²) (all masses of explosive)
0	2029	961
0.05	2356	1747
0.10	2480	2145
0.15	2524	2301
0.20	2534	2338
0.25	2530	2323
0.30	2121	1147
0.40	1708	483
0.50	1488	278
0.60	1353	190
0.70	1266	146
0.80	1208	121
0.90	1172	107
1.00	1153	100

Table 1
Fireball temperature and heat flux profile for TNT predicted by heat loss model

Table 2 Damage and casualties in dwelling houses in World War 2 air raids on Britain: injury as a function of distance for 12 V-2 incidents

Distance from burst (ft)	No. of casualties					
	K	SI	LI	U	K+SI	K+SI+LI
0-10	7	0	0	0	7	7
10-20	7	0	0	0	7	7
20-30	7	1	0	0	8	8
30-40	12	4	3	4	16	19
40-50	19	4	2	6	23	25
50-60	23	1	9	4	24	33
60-70	21	4	6	11	25	31
70-80	5	1	8	18	6	14
80-90	3	2	10	27	5	15
90-100	3	7	17	45	10	27
100-125	5	5	16	101	10	26
125-150	0	10	21	142	10	31
150-175	0	4	10	210	4	14
175-200	0	2	14	258	2	16

Table 2 Damage and casualties in dwelling houses in World War 2 air raids on Britain: injury as a function of distance for 12 V-2 incidents

Table 3 Damage and casualties in dwelling houses in World War 2 air raids on Britain: injury as a function of damage category for 12 V-2 incidents

Housing damage category	Observed ACR (ft)	No. at risk	No. of casualties			Probability of injury		
			K	K+SI	K+SI+LI	P(K) (%)	P(K+SI) (%)	P(K+SI+LI) (%)
A _b	30	22	21	22	22	95.5	100	100
A _a	68.9	128	72.5	85.1	104.4	56.6	66.4	81.5
B	102	162	13.9	24.7	61.6	8.6	15.2	38.0
C _b	178	540	4.6	23.4	70.4	0.9	4.3	13.0
C _a	511	6311	0	12.8	39.7	0	0.2	0.6
D	1020	21492	0	1	7.9	0	0	0

Table 3 Damage and casualties in dwelling houses in World War 2 air raids on Britain: injury as a function of damage category for 12 V-2 incidents

Table 4 Standardised Casualty Rates in World War 2 air raids on Britain: SKHCR by type of exposure for all weapons

	In open	Location		In shelters	All exposures
		In dwellings	In other buildings		
SKHCR	18.85	5.31	5.45	1.94	5.07
Ratio(a)	3.55	1.00	1.03	0.37	0.95

Source: *Textbook of Air Armaments*²⁴: Table 35

(a) Ratio of other exposures to that in dwellings.

Table 4 Standardised Casualty Rates in World War 2 air raids on Britain: SKHCR by type of exposure for all weapons

Table 5 Probabilities of injury vs distance to persons exposed outdoors from explosion of a single unit of six of Mk82 bombs

A Physical effects and damage

Distance	Physical effects Blast Peak overpressure	Positive impulse	Peak dynamic pressure load	Fireball Thermal radiation	Damage Window breakage
(m)	(kPa)	(kPa.ms)	(kPa)	(s.(W/m ²) ^{4/3})	(%)
20-25	149	121	65	0.40 x 10 ⁸	100
25-30	98	101	30	0.24 x 10 ⁸	100
30-35	70	87	16	0.15 x 10 ⁸	100
35-40	54	77	9.5	0.11 x 10 ⁸	100
40-45	43	69	6.1	0.77 x 10 ⁷	100
45-50	36	63	4.2	0.57 x 10 ⁷	100
50-55	30	57	3.1	0.44 x 10 ⁷	100
55-60	26	53	2.3	0.35 x 10 ⁷	98
60-65	23	49	1.8	0.28 x 10 ⁷	98
65-70	20	45	1.4	0.23 x 10 ⁷	98
95-100	12	32	0.52	0.86 x 10 ⁶	92
145-150	7.2	22	0.18	0.29 x 10 ⁶	80
195-200	5.0	16	0.09	0.13 x 10 ⁶	68

Table 5. Probabilities of injury vs. Distance to persons exposed outdoors from explosion of a single unit of six of Mk82 bombs

B Direct blast injury, falling debris and bodily displacement

Distance (m)	Injury Persons near buildings		Falling debris		Persons away from buildings		Bodily displacement		
	Lung haemorrhage K (%)	Eardrum rupture (%)	K (%)	K+SI (%)	Lung haemorrhage K (%)	Eardrum rupture (%)	K (%)	K+SI (%)	Blown over (%)
20-25	8.8	84	50	75	0	71	0	1.5	100
25-30	0	63	1	25		46		0	100
30-35		43	1	25		28			100
35-40		28	0	1		16			100
40-45		18		1		9.0			89
45-50		11		1		5.1			57
50-55		7		1		3			21
55-60		5		1		1.8			4.7
60-65		3		0		1.1			0
65-70		2				0			0
95-100		0							

Table 5. Probabilities of injury vs. Distance to persons exposed outdoors from explosion of a single unit of six of Mk82 bombs

C Other injury modes and casualty summary

Distance (m)	Injury Burn injury			Injury by crater ejecta K+SI	Injury by primary fragments			Overall fatalities	
	K	2nd degree	1st degree		K	K+SI	K+SI+LI	Persons near near buildings K	Persons away from buildings K
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
20-25	3	100	100	1.6	30.6	32	33	68	31
25-30	3	100	100	1.1	25	30	32	26	25
30-35	2.9	96	99	0.8	20	27	31	21	20
35-40	2.3	75	99	0.6	16	24	28	16	16
40-45	0.9	29	75	0.3	9.8	16	20	9.8	9.8
45-50	0.2	6.8	55	0.2	5.9	9.9	13	5.9	5.9
50-55	0.03	1.0	39	0.1	3.5	6.2	8.4	3.5	3.5
55-60	0	0	26	0.1	2.2	4.0	5.5	2.2	2.2
60-65			17	0.05	1.6	2.9	4.1	1.6	1.6
65-70			9.8	0.04	1.2	2.3	3.3	1.2	1.2
95-100			0	0.02	0.55	1.1	1.6	0.55	0.55
145-150			0.004		0.22	0.45	0.69	0.22	0.22
195-200			0.002		0.12	0.26	0.39	0.12	0.12

K is killed

K+SI is killed + seriously injured (hospitalised)

K+SI + LI is killed + seriously injured + slightly injured (hospitalised)

Table 5. Probabilities of injury vs. Distance to persons exposed outdoors from explosion of a single unit of six of Mk82 bombs

FIGURE 1

Some principal effects of a condensed phase explosion involving a charge of munitions on a vehicle, including the blast wave; fireball; ground shock; cratering and crater ejecta; primary fragments from the casing and the vehicle itself; displacement of persons; window damage and flying glass; and falling debris and falling glass

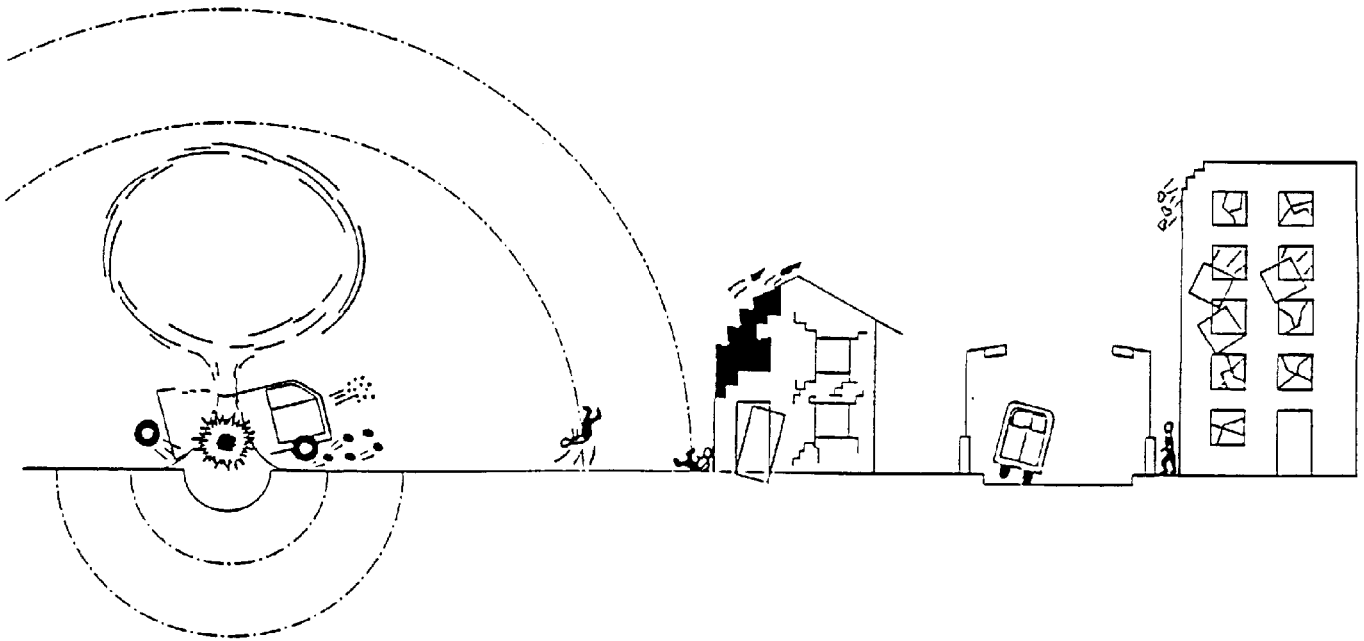


Figure 1 Some principal effects of a condensed phase explosion involving a charge of munitions on a vehicle, including the blast wave; fireball; ground shock; cratering and crater ejecta; primary fragments from the casing and the vehicle itself; displacement of persons; window damage and flying glass; and falling debris and falling glass

FIGURE 2 Structure of the overall explosion model

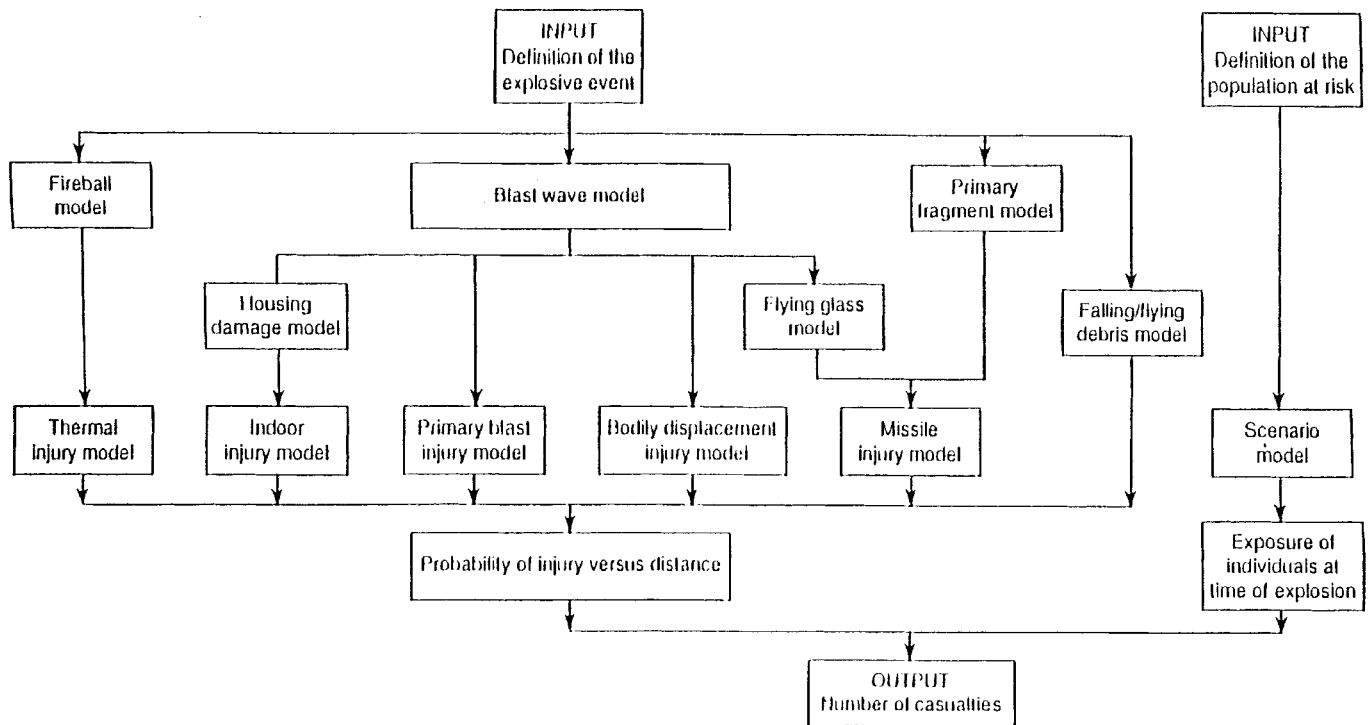


Figure 2 Structure of the overall explosion model

FIGURE 3
Stages of development of fireball: (a) initial charge; (b) end of Stage I; (c) end of Stage 2; (d) early in Stage 3, following transformation from hemispherical to spherical shape; (e) end of Stage 3, at point of extinction

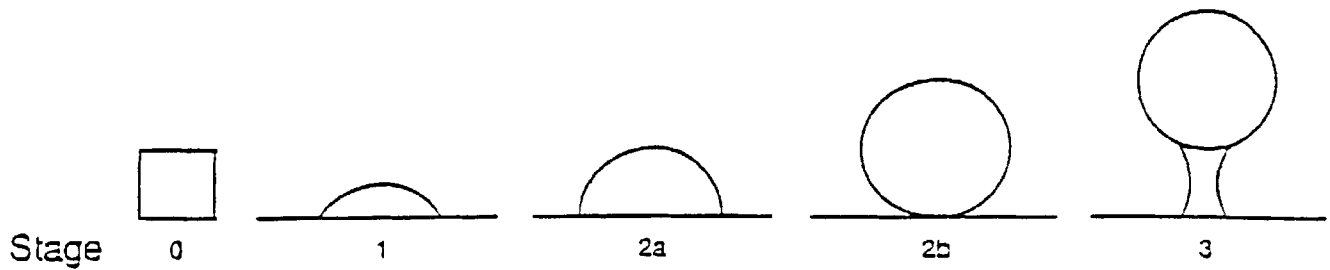


Figure 3 Stages of development of fireball: (a) initial charge; (b) end of Stage 1; (c) end of Stage 2; (d) early in Stage 3, following transformation from hemispherical to spherical shape; (e) end of Stage 3, at point of extinction

FIGURE 4
Profiles of the temperature of the fireball from initiation of 10^4 kg
of four different explosives

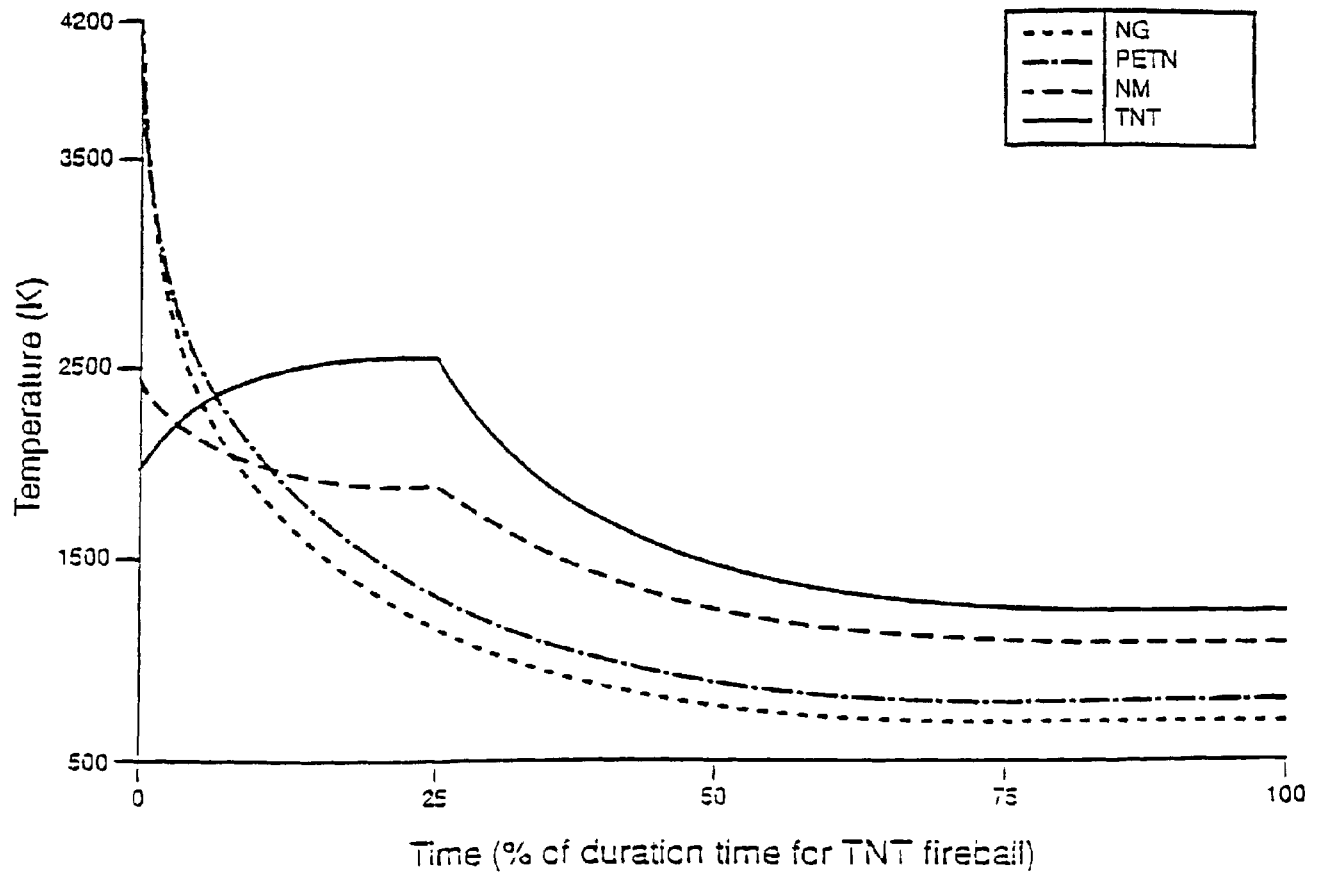


Figure 4 Profiles of the temperature of the fireball from initiation of 10^4 kg of four different explosives

FIGURE 5

Model predictions for average number of fatal injuries to persons exposed indoors in an explosion of an explosive load (TNT equivalent) in a built-up area: K=killed; SI=seriously injured; LI=lightly injured

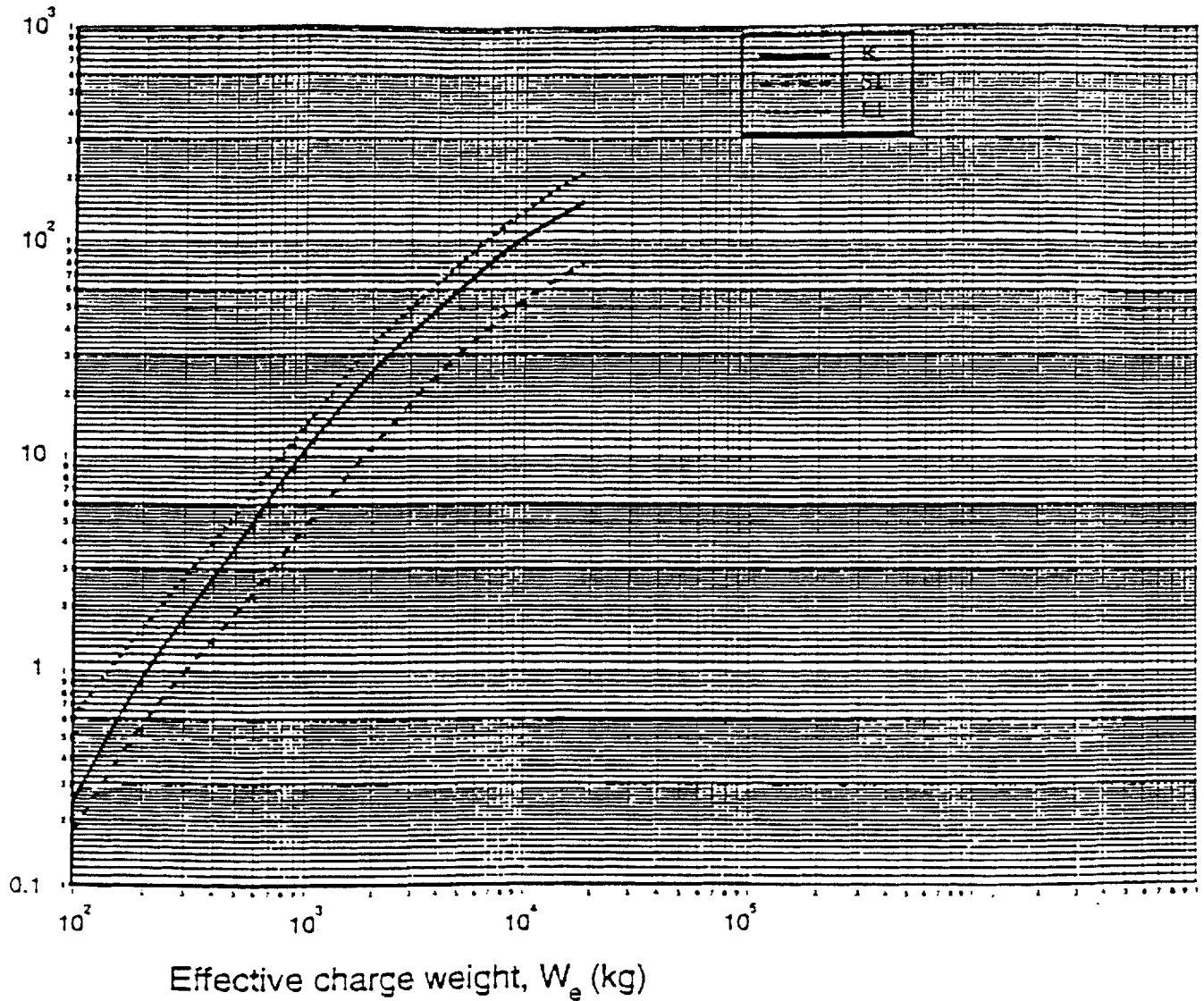


Figure 5 Model predictions for average number of fatal injuries to persons exposed indoors in an explosion of an explosive load (TNT equivalent) in a built-up area: K=killed; SI=seriously injured; LI=lightly injured