Journal of Hazardous Materials, 33 (1993) 1–33
Elsevier Science Publishers B.V., Amsterdam

A guide to the evaluation of condensed phase explosions

P.A. Davies

Four Elements Ltd., Greencoat House, Francis Street, London SW1P 1DH (UK)

(Received March 9, 1992; accepted June 5, 1992)

Abstract

Condensed phase explosives present a hazard to both property and people. This hazard, which primarily manifests as overpressure, fragment generation and/or thermal radiation, can be realised through accidental initiation during manufacture, storage, handling and transport. Much work has been conducted to understand and quantify the effects of hazard realisation on property and people. This paper reviews available literature, describes a number of models, details damage criteria and provides an overview of condensed phase explosion effects on property and people.

1. Introduction

Damage caused to both property and people, as a result of explosion, often requires detailed evaluation so that action can be taken to reduce consequences, measures can be enacted to limit the likelihood of explosion and credible risk assessments can be performed. The following chapters describe explosion consequences and illustrate how certain effects can be quantified.

Since the beginning of the 1950's the majority of work in condensed phase (CP) explosion theory and effects has concentrated on nuclear explosions. However, the damage caused by nuclear explosions is not easily extrapolated to the damage associated with CP explosions. This is because explosions are essentially yield related. Consequently, thermal and pressure impulses differ between nuclear and CP explosions, and hence each type of explosion produces different degrees of damage. As a consequence of this it is difficult to compare nuclear explosions, having typical yields of 100,000 tonnes or more, with low yield CP explosions of interest in the manufacture, transport and storage of condensed phase explosives. In addition, data from nuclear explosions include the effects of ionising radiation together with other nuclear peculiarities, such as, thermo-nuclear pulse. As an example of their differences consider the case

---

Correspondence to: Dr. P.A. Davies, Four Elements Ltd., Greencoat House, Francis Street, London SW1P 1DH (UK). Current address: Europa House, 310 Europa Blvd., Westbrook, Warrington, WA5 5YQ (UK).

of nuclear and conventional fireballs. The black body temperatures of nuclear initiated fireballs are orders of magnitude greater than their CP counterparts. Radiation temperatures for nuclear explosions approximate to 10^7 K, which is over 2000 times that of many high explosive and propellant explosions [1]. Similarly, nuclear weapons emit energy in the range 0.01 nm to 10 nm compared with 200 nm to 500 nm for conventional explosives.

In conclusion, there are no simple scaling laws which can be used to relate CP and nuclear explosions, or simple means of isolating ionising effects etc., so that data can be readily extrapolated. Consequently, the following chapters, where possible, only refer to CP explosions. This is because the inclusion of nuclear data may lead to erroneous assumptions and conclusions being made on the effects of relatively low yield chemical explosions.

2. Blast damage and injury

The term blast wave is used here to mean the shock wave caused by an explosion and should not be confused with the detonation wave. Upon detonation a detonation shock front travels away from the charge causing the temperature of the surrounding air to rise [1]. This initial shock front is known as the detonation wave. After a short distance of travel the detonation wave is overtaken by a new shock front which leaves a zone of rarefied air immediately behind it. This new shock front is known as the blast wave and although its peak pressure and initial velocity is lower than that of the detonation wave it decays much more gradually and therefore exerts its force over a greater distance [1]. The blast wave from all chemical explosions has a definite and measurable pattern. Upon detonation a sudden and violent release of energy causes the surrounding air pressure to rise rapidly creating a region of positive pressure known as “overpressure”. As the blast wave moves away from its source at high velocity (supersonic) the overpressure increases sharply to a peak value, known as the peak overpressure, and then gradually recedes. The overpressure phase is followed by a region of negative pressure or “underpressure”. This pressure is generally insignificant compared with the overpressure phase, although such negative pressure can cause moderate damage especially at close distances from the charge.

The characteristics of blast waves are discussed by Lees [2] and detailed accounts are given by Kinney [3] and Baker et al. [1]. It is sufficient here to simply identify a means by which blast wave characteristics, in particular overpressure, can be estimated so that their effects on buildings and people can be quantified.

Damage and injury as a result of explosion is largely a consequence of two loading effects, known as diffraction and drag. Diffraction loading is related to the peak overpressure of a blast wave as it passes over and around an object or structure. Peak overpressure refers to the pressure above ambient at a given location (often termed side-on overpressure). In this instance overpressure refers to the pressure above ambient upon blast wave interaction with an object or structure. Diffraction loading refers to the force exerted on an object or structure during blast wave envelopment. The loading consists of two components; firstly, that resulting from the pressure differential that exists between the front and back of an object/structure prior to envelopment and secondly, static loading ("crushing" forces) due to the pressure differential between internal and external environments. The process of envelopment is described in detail by Glasstone and Dolan [4]. Essentially, upon striking an object or structure blast wave reflection occurs. This not only changes blast wave direction but also its momentum as it collides with the "winds" following its passage. Such collision results in a rapid rise in pressure termed the reflected overpressure. As the pressure drops the blast wave bends or "diffracts" over and around the structure loading other faces. In comparison, drag loading is related to dynamic pressure. This is the air pressure behind a shock front and unlike overpressure has no reference to ambient pressure. Forces exerted by drag loading are the result of transient winds which accompany the passage of a blast wave.

For very large explosions (peak overpressure greater than about 4.8 bar) dynamic pressure is greater than peak overpressure. As a consequence of this drag loading tends to be the main cause of damage in large explosions. This can also be the case where objects and structures present little resistance to blast waves. For example, buildings whose walls, windows and doors rapidly fail during blast wave interaction cause prompt equalisation of interior and exterior environments. This in turn can reduce the duration and magnitude of diffraction loading to a negligible level [4]. (This is one means by which the effects of diffraction loading can be minimised.) For the types of explosions considered here peak overpressure is greater than dynamic pressure and therefore damage is largely the result of diffraction loading. However, this is not always true. It should be noted that all objects and structures simultaneously suffer both diffraction and drag loading. This is because overpressure and dynamic pressure both exist during blast and cannot be separated. The relative importance of each load type is largely dependent on size, shape, weight and resistance of objects and structures. Closed or semi-closed structures, such as buildings with small openings or large tanks, etc. are vulnerable to diffraction loading, whereas, tall thin objects and buildings with large openings are vulnerable to drag loading. The discussion given here, together with Table 1, provides a rough guide in judging the type of load most important to particular objects and structures. A detailed appraisal of the behaviour of objects and structures to diffraction and drag loading is given by Glasstone and Dolan [4].

Blast wave damage is most commonly related to overpressure. This is probably due to its ease of measurement and estimation compared with other damage-relation criteria. However, blast wave damage is also a function of rate of pressure rise and wave duration. As a consequence of this, impulse is also used as a measure of blast damage. Impulse is a function of both overpressure

TABLE 1

Principal loading vulnerability of structures and objects (after Glasstone and Dolan [4])

Structures susceptible to diffraction loading	Structures and objects susceptible to drag loading
Multi-storey reinforced concrete buildings with concrete walls, small window areas, 3–8 storeys	Light steel frame industrial buildings, low strength walls which quickly fail, single storey
Multi-storey wall-bearing buildings, brick apartment houses, up to 3 storeys	Heavy steel frame industrial buildings, lightweight low strength walls which quickly fail, single storey
Multi-storey wall-bearing buildings, monumental types, up to 4 storeys	Multi-storey steel frame office-type building, lightweight low strength walls which quickly fail, both earthquake and non-earthquake resistant, 3–10 storeys
Wood frame buildings, house types, 1 or 2 storeys	Multi-storey reinforced concrete frame office-type building, lightweight low strength walls which quickly fail, both earthquake and non-earthquake resistant, 3–10 storeys.
Highway and railroad bridges	Telegraph poles, electricity pylons
	Transport equipment and vehicles
	Trees and vegetation

and wave duration and therefore is often considered a better measure of blast wave damage. However, using impulse as a damage-relation criterion can cause confusion. For example, based solely on impulse, blast waves may be assumed to have certain damage potential but in fact be unable to deliver this due to insufficient overpressure [1, 5]. Overpressure itself is not an entirely satisfactory measure of blast damage. This fact has been acknowledged and has led to the development of pressure–impulse correlations commonly known as P–I diagrams or curves. Similarly, distance–charge relationships have been derived (R–W correlations) relating distance and yield to structural response. Unfortunately, both of these techniques suffer from lack of usable data. This is not to say that the techniques are ineffective or unusable, current opinion suggests that P–I and R–W correlations provide improved means of assessing blast damage compared with the traditional overpressure–damage relation [1, 5].

It is apparent that blast damage is not adequately defined by a single parameter, but P–I and R–W correlations, have as yet, limited use due to lack of data. Attempting to relate a number of criteria to the assessment of blast damage is not new. Limits of damage with respect to peak overpressure were suggested by Robinson [6] as long ago as 1944, and more recently by the Explosives Storage and Transport Commmittee [7] (ESTC). The empirical relationship devised by the ESTC and described by Jarrett [7] is the foundation of the British Safety Distances for military and commercial explosives [5]. Basically blast damage is split into various categories and each category related to yield, distance and housing damage. These relationships and damage categories are illustrated here in Table 2. Using the work described by Jarrett and that of Assheton [8], Scilly and High [5] illustrate not only damage with respect to overpressure and damage category (described by Jarrett [7]) but also with respect to the mass of explosive consumed. The data given by Scilly and High are reproduced here in Table 3. For further detail on damage categories reference should be made to the original work of Jarrett [7].

From the discussion given above, and the fact that much work relating overpressure and blast damage has been performed and recorded, for most practical purposes overpressure provides a good estimation of blast wave damage. An additional reason for the adoption of overpressure as the primary measure of blast damage is possibly due to the fact that in addition to diffraction loading, drag loading can also be related to peak overpressure. This is because the dynamic pressure associated with drag loading is a function of wind speed and air density (behind the shock front) and both of these can be related to peak overpressure [4].

TABLE 2

Housing damage categories in relation to the distance from condensed explosions (after Jarrett [7])

Damage category (constant K)[a]	Description
A (3.8)	Almost complete demolition
B (5.6)	50–75% external brickwork destroyed or rendered unsafe, requiring demolition
Cb (9.6)	Houses uninhabitable — partial or total collapse of roof, partial demolition of one or two external walls, severe damage to load-bearing partitions requiring replacement
Ca (28)	Not exceeding minor structural damage, and partitions and joinery wrenched from fixings
D (56)	Remaining inhabitable after rapair — some damage to ceilings and tiling, more than 10% window glass broken

[a] $R = \dfrac{KW^{1/3}}{[1 + (3175/W^2)]^{1/6}}$, where R is the distance from condensed explosion (m), W the mass of explosive (kg) and K a constant. Note that "R" defines the average radii for idealised circles within which dwellings suffer the damage associated with a chosen category. Those dwellings that suffer damage for a given category outside the circle are balanced by those within the circle which do not suffer such damage. (The formula and constants are given in imperial units by Jarrett.)

TABLE 3

Explosion damage with respect to overpressure, degree of damage and mass of explosive consumed (after Scilly and High [5])

Structure or object	Damage	Approximate peak overpressure (bar)[a]		
		1 tonne	10 tonne	100 tonne
Window panes	5% broken	0.010	0.007	0.007
	50% broken	0.025	0.017	0.014
	90% broken	0.062	0.041	0.037
Houses	Tiles displaced	0.044	0.029	0.026
	Doors and window frames may be blown in	0.090	0.059	0.053
	Category D damage	0.045	0.030	0.029
	Category Ca damage	0.124	0.079	0.076
	Category Cb damage	0.276	0.165	0.159
	Category B damage	0.793	0.359	0.345
	Category A damage	1.827	0.793	0.758
Telegraph poles	Snapped	3.585	1.793	1.655
Large trees	Destroyed	3.930	1.793	1.655
Primary missiles	Limit of travel	0.014	0.010	0.008
Rail wagons	Limit of derailment	1.827	0.793	0.758
	Bodywork crushed	1.379	0.600	0.579
	Damaged but easily repairable	0.793	0.393	0.379
	Superficial damage	0.317	0.179	0.172
Railway Line	Limit of destruction	14.13	6.688	6.412

[a] All distances (overpressures) from the explosion source are measured to the furthest point of the structure or object (overpressures originally estimated in imperial units, psi).

As a consequence of all the factors discussed above overpressure is used henceforth to describe blast damage. For further details on the rate of pressure rise, wave duration, pressure-impulse and distance-charge correlations (in relation to blast damage) reference should be made to either Baker et al. [1], Kinney [3], Scilly and High [5], Baker [9] or Glasstone and Dolan [4].

A multitude of scaling laws has been devised which relates blast overpressure, charge size and distance etc.. A number of these are discussed by Baker [9]. Far the most popular and widely used is based on the "principle of similarity" proposed by Hopkinson in 1915 (see Turnbull and Walter [10]). Provided the scales used to measure blast from any explosive are altered by the same factors as the dimensions of the relative charges then the properties will be similar. Rather than use the dimensions of the charge it is more practical to use charge weight and assume that explosive charges are compact and symmetrical. This method has been used to develop what is commonly known as the "cube root" law. Based on the fact that overpressure is related to distance, the scaled distance, Z, at which peak overpressure is known can be found.

$$Z = R/W^{1/3} \tag{1}$$

where Z is the scaled distance (m/kg$^{1/3}$), R the distance from charge (m) and W the charge size (kg).

Strictly the scaling law is based on available energy. However, for simplicity it is assumed that the energy released is proportional to the mass of explosive.

Using the scaled distance in conjuction with Fig. 1 the peak overpressure at distance, R, can be estimated. The graph of peak overpressure vs. scaled distance, shown in Fig. 1, is taken from Lees [2] and is based on data given by Baker [9] for the explosion of TNT. Similar graphs are given by Kinney [3], Brasie and Simpson [11] and Stull [12] and more complex ones by Baker [9]. However, the graph presented here is considered to be a good approximation of peak overpressure with respect to scaled distance. This is because the values obtained from it tend to correspond well with other works [3, 11, 12].

Before further discussing the effects of blast it should be noted that the terms "primary", "secondary" and "tertiary" are not well defined in the literature. Workers appear to use the terms differently. So as to avoid confusion, in this chapter primary refers to all effects directly attributable to the blast wave (e.g. lung haemorrhage and eardrum rupture), secondary refers to all indirect effects such as missile impact and tertiary refers to the damage associated with bodily translation.

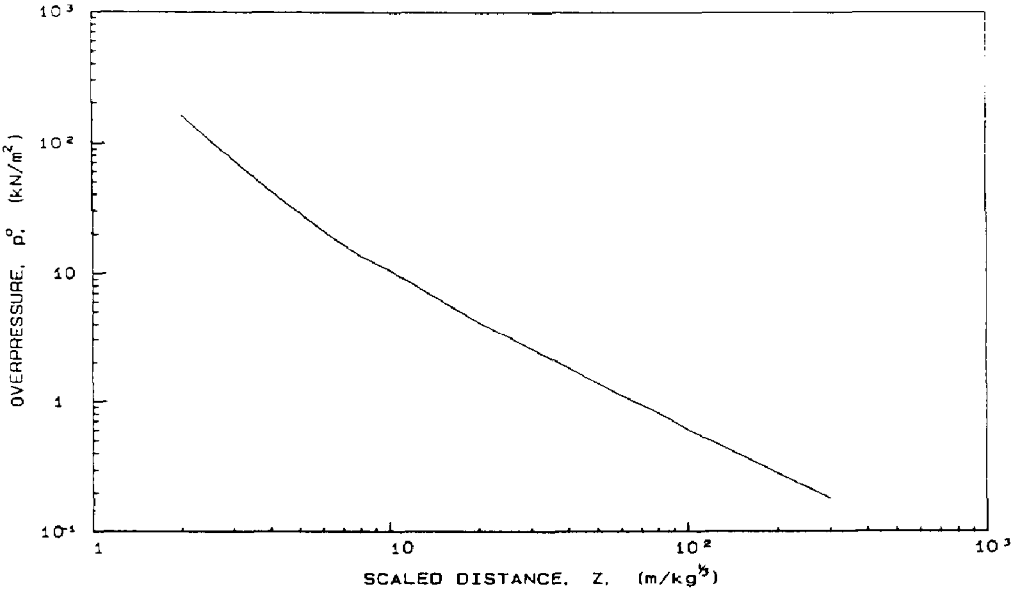

Fig. 1. Peak overpressure vs. scaled distance

Blast damage can effectively be divided into two discrete categories, namely, building damage and human damage. With respect to building damage large amounts of data exist describing and quantifying the effects of overpressure. Robinson [6] provides an extensive analysis of minor and serious damage resulting from blast and Eisenberg et al. [13], using data supplied by Fugelso et al. [14], derive probit equations relating structural damage to peak overpressure. A summary of blast damage with respect to peak overpressure is given by Clancey [15]. This summary is based on work reported by Braise and Simpson [11] and is reproduced here in Table 4. Generally an overpressure of 0.07 bar (1 psi) is considered sufficient to cause partial demolition of typical British brick and concrete constructions, whereas, 0.70 bar (10 psi) is taken as resulting in total demolition. However, these figures are not agreed upon by all. Turnbull and Walter [10] quote 1.5 bar as the onset of considerable building damage. This disagreement may well stem from the omission of certain blast criteria. Unlike human damage, the estimation of building damage tends to be sensitive to the response time of structures and blast reflection. Regardless of these additional criteria it is generally considered that overpressure is adequate in assessing building damage.

Human damage, or as it is more commonly termed injury, is either due to direct blast wave contact or secondary effects, such as, whole body translation and missile impact. The most susceptible parts of the body to blast damage are those organs possessing large density differences amongst neighbouring tissue [16]. As a consequence of this most deaths from blast overpressure (i.e. primary effects) are a result of lung haemorrhage and heart failure. In comparison, minor injury is often based on eardrum rupture, since the ear, although not a vital organ is exceptionally sensitive to pressure. An increase in pressure of only 2×10^{-5} N/m^2 (2.9×10^{-9} psi) will cause the eardrum to move less than the diameter of a single hydrogen molecule [17]. Eisenberg et al. [13] have derived probit equations relating peak overpressure to the likelihood of death. The probit is based on lung haemorrhage and is given by

$$Pr = -77.1 + 6.91 \ln P^{\circ} \qquad (2)$$

where Pr denotes the probit (originally given as Y), and P° is the peak overpressure (N/m^2).

Similarly, they derive a probit equation for minor injury based on eardrum rupture.

$$Pr = -15.6 + 1.93 \ln P^{\circ} \qquad (3)$$

A sample of the results gained using these equations is given in Tables 5 and 6. The equations were developed for early risk assessments and still remain popular although their accuracy has been questioned.

Predicting lung haemorrhage and eardrum rupture is an extremely difficult task and many researchers present differing results. In comparison to the results given by Eisenberg et al. [13] shown in Tables 5 and 6, Turnbull and

TABLE 4

Damage produced by blast (after Clancey [15])

Pressure (bar)	Damage
0.0014	Annoying noise (137 dB), if of low frequency (10–15 Hz)
0.0021	Occasional breaking of large glass windows already under strain
0.0028	Loud noise (143 dB). Sonic boom glass failure
0.0069	Breakage of windows, small, under strain
0.010	Typical pressure for glass failure
0.020	"safe distance" (probability 0.95 no serious damage beyond this value). Missile limit (some damage to house ceilings; 10% window glass broken)
0.028	Limited minor structural damage
0.034–0.069	Large and small windows usually shattered; occasional damage to window frames
0.048	Minor damage to house structures
0.069	Partial demolition of houses, made uninhabitable
0.069–0.138	Corrugated asbestos shattered. Corrugated steel or aluminium panels, fastenings fail, followed by buckling. Wood panels (std. housing) fastenings fail, panels blown in
0.090	Steel frame of clad building slightly distorted
0.138	Partial collapse of walls and roofs of houses
0.138–0.207	Concrete or cinder block walls, not reinforced, shattered
0.159	Lower limit of serious structural damage
0.172	50% destruction of brick work of house
0.207	Heavy machines (3000 lb) in industrial building suffered little damage. Steel frame building distorted and pulled away from foundations
0.207–0.276	Frameless, self-framing steel panel building demolished. Rupture of oil storage tanks
0.276	Cladding of light industrial buildings ruptured
0.345	Wooden utilities poles snapped (telegraph poles, etc.) Tall hydraulic press (40,000 lb) in building slightly damaged
0.345–0.483	Nearly complete destruction of houses
0.483	Loaded train wagons overturned
0.483–0.552	Brick panels, 8–12 in. thick, not reinforced, fail by shearing or flexure
0.621	Loaded train box-cars completely demolished
0.689	Probable total destruction of buildings. Heavy machine tools (7000 lb) moved and badly damaged. Very heavy machine tools (12,000 lb) survived
20.68	Limit of crater lip

TABLE 5

Probability of fatality from lung haemorrhage for a given overpressure (after Eisenberg et al. [13])

Probability of fatality (%)	Peak overpressure	
	(bar)	(psi)
1	1.00	14.5
10	1.20	17.5
50	1.40	20.5
90	1.75	25.5
99	2.00	29.0

TABLE 6

Probability of eardrum rupture for a given overpressure (after Eisenberg et al. [13])

Probability of eardrum rupture (%)	Peak overpressure	
	(bar)	(psi)
1	0.17	2.4
10	0.19	2.8
50	0.44	6.3
90	0.84	12.2

Walter [10] quote a figure of 3 bar rather than 1.4 bar as the pressure needed to cause 50% fatalities from lung haemorrhage. Similarly, Baker et al. [1] using the results of Vadala [18], Henry [19] and Reider [20] have produced a plot of the percentage of eardrum ruptures vs. peak overpressure. From the plot they estimate that the probability of eardrum rupture at 1 bar (14.5 psi) is approximately 50% and not 90% as given by Eisenberg et al. The plot presented by Baker et al. is reproduced here in Fig. 2. More recently Pietersen [21] has described probit relations derived by TNO [22] for the estimation of injury based on lung haemorrhage and eardrum rupture. The probits are derived in part from the abundance of work performed on explosion effects at the Lovelace Foundation [23] in the US during the 1950's and 1960's, in particular the work performed by Bowen et al. [24], Fletcher and Bowen [25], White [16] and Hirsch [26]. The probits based on lung haemorrhage and eardrum rupture illustrated by Pietersen provide similar results (marginally lower) to those given by Eisenberg et al. [13] and are therefore not detailed here.

Death and non-fatal injury from secondary effects, as previously stated, is generally the result of bodily translation or missile contact. The effects of

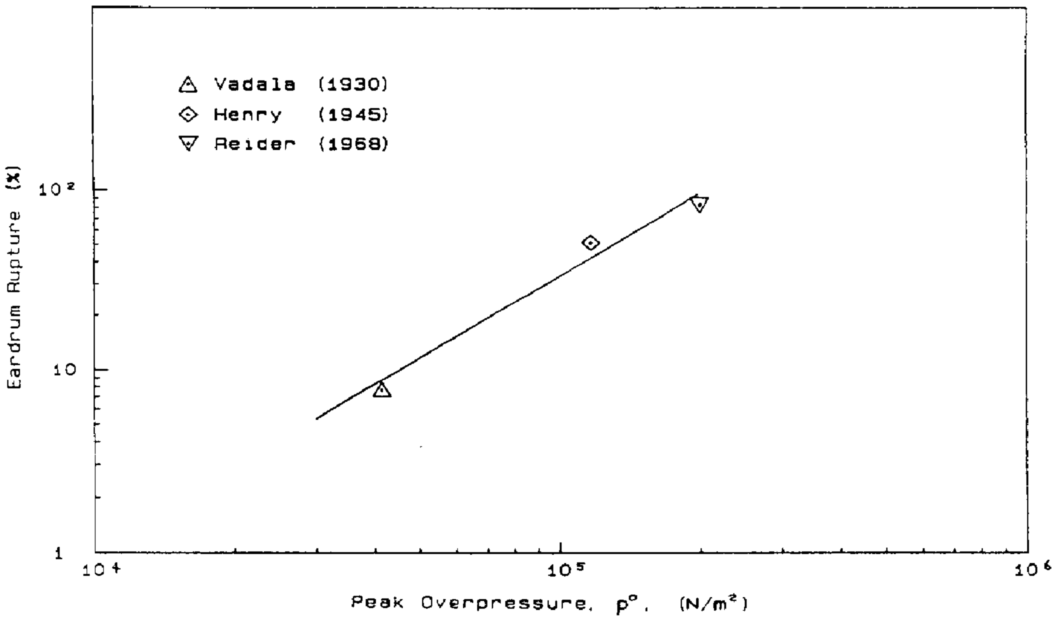

Fig. 2. Eardrum ruptures (%) vs. overpressure (after [18–20]).

missiles on the human body are dealt with in Chapter 3.0 and are not discussed here. Bodily translation consists of displacement and subsequent decelerative impact with the ground, building materials and/or other objects. Damage occurs as a result of the head or other vulnerable body parts colliding with hard surfaces causing fracture, concussion and/or haemorrhage (known as tertiary damage). The degree of injury is related to impact velocity, duration, terrain, distance thrown, impacting surface and orientation. Baker and Oldham [27] have developed a method of quantifying damage caused by bodily translation based on specific impulse and incident overpressure. Using the method together with data gained through White [16] and Clemedson et al. [28] tertiary damage is expressed in terms of impact velocity. Abstracted results from Baker and Oldham [27] are given in Tables 7 and 8. Longinow et al. [29] have also estimated tertiary damage. They derive a relationship between the probability of death and impact velocity. A graphical representation of the relationship is reproduced here in Fig. 3. It can be seen that the values given by Baker and Oldham correspond well with the relationships given by Longinow et al. for skull and whole body impact.

Other characteristics associated with blast waves, such as, toxic gases, ground shock and crater are considered here to be insignificant compared with those effects described above. This is because such phenomena only become a serious hazard in exceptionally large or confined (toxic gases) explosions. Additionally, the likelihood of death or injury from such effects is small compared with death or injury from direct and indirect blast effects. Therefore, the effects of toxic gases, ground shock and crater are not discussed here.

TABLE 7

Criteria for tertiary damage (decelerative impact) to the head (after Baker et al. [1, 27])

Skull fracture tolerance	Related impact velocity (m/s)
Mostly "safe"	3.05
Threshold	3.96
50 percent	5.49
Near 100 percent	7.01

TABLE 8

Criteria for tertiary damage involving total body impact (after Baker et al. [1, 27])

Total body impact tolerance	Related impact velocity (m/s)
Mostly "safe"	3.05
Lethality threshold	6.40
Lethality 50 percent	16.46
Lethality near 100 percent	42.06

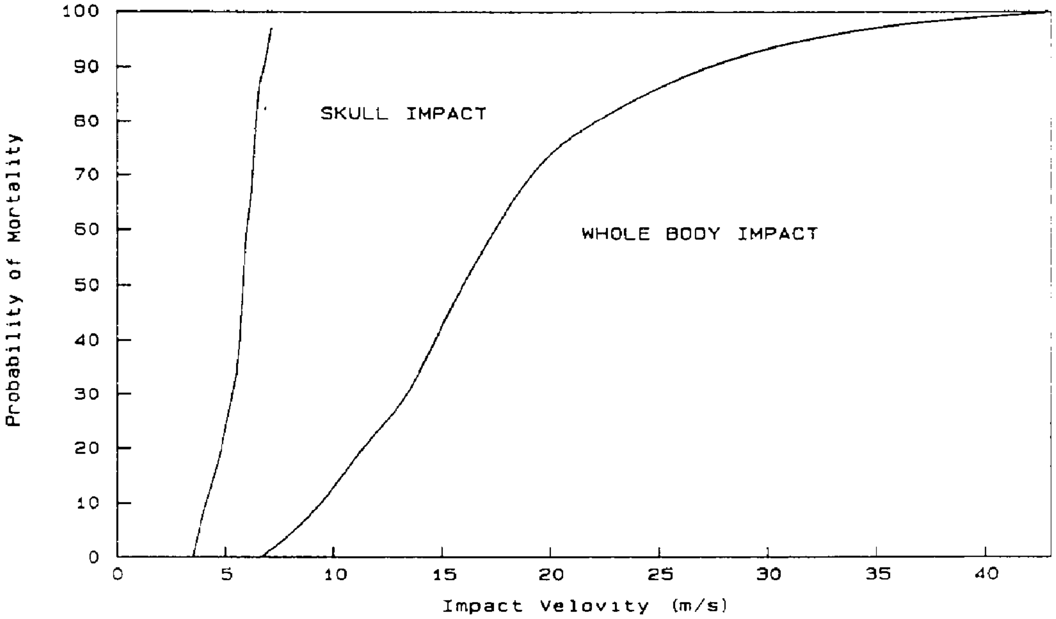

Fig. 3. Fatality criterion: Bodily translation (after [29]).

Further information, with respect to these phenomena can be gained through Lees [2], Robinson [6], Clancey [15] and Pietersen [21].

3. Missile damage and injury

Fragment generation, as a result of explosion, can produce significant damage to receiving medium. Energy delivered to fragments from blast waves cause fragments to become airborne and act as missiles characterised by velocity, range and penetration. Such missiles are often classed as being either primary or secondary [1]. Primary missiles consist of casing and/or container fragments from the explosive item, whereas, secondary missiles consist of fragments from objects located close to the explosion source which have interacted with the blast wave.

Unlike the one or two large fragments which result from typical storage vessel "bursts" [1, 30], the casings and packages of high explosives rupture into large numbers of small primary fragments. Although the fragments are small and irregular, they are generally of a "chunky" appearance (inasmuch that all linear dimensions are of a similar magnitude) and for typical shell casings weigh in the region of one gram [31, 32]. In addition, high explosive primary missiles have velocities over ten times that of typical pressure burst fragments; velocities approaching several thousand metres per second are not uncommon [31].

Secondary missiles, as mentioned above, are the result of blast wave interaction with objects located near to the source of explosion. Such fragments are often termed as being either "constrained" or "unconstrained". The terminology depends upon whether the blast wave tears them from their fixings [1] or simply "up-roots" them from their position. The fragments may take a multitude of forms from building materials through to vegetation. Velocity, range and penetration of secondary missiles are, in the main, much less than those of primary types. However, it is not unknown for blast waves to accelerate secondary fragments to velocities where they become capable of inflicting serve impact damage [1, 32].

It is not the intention of this work to explain in-depth the means of calculating, from accidental explosions, missile projectory, penetration, range or velocity. Much work has already been done on these subjects. A brief description is given by Lees [2] and detailed accounts by Baker et al. [1], Clancey [15] and High [33]; all of these contain references to other works. However, for completeness a brief description of the methods used to calculate missile velocity, range and penetration is included here.

Missile velocity can be estimated through the consideration of explosion energy. For typical fragments from cased [2] charges initial fragment energy varies from between 20% and 60% of the explosion energy. Initial fragment velocity can be calculated from

$$E=\tfrac{1}{2}MV^2 \qquad (4)$$

where E is the initial kinetic energy of the fragment (J), M fragment mass (kg), and V the initial fragment velocity (m/s).

Clancey [15] estimates that for the majority of fragments, resulting from TNT explosions, fragment velocities are as follows: Thin case 8000 ft/s (2438 m/s), medium case 6000 ft/s (1829 m/s), and thick case 4000 ft/s (1219 m/s).

The velocities have been estimated from empirical data on the assumption that any size charge will propel fragments the same distance. Although this assumption is untrue, since large explosions propel fragments further than small explosions, the estimates do assist in preliminary analysis. Clancey [15] also details an empirical calculation of missile range. Modifying the formula in order to incorporate SI units, the range is given by

$$X=(W^{1/3}/ka)(\ln U/V) \tag{5}$$

where X denotes the range (m), W fragment mass (kg), U initial fragment velocity (m/s), V fragment velocity (m/s), k is a constant (0.002 velocity supersonic, 0.0014 velocity subsonic) ($\mathrm{kg}^{1/3}/\mathrm{m}$), and a is the drag coefficient.

Drag coefficients are a function of fragment shape and orientation during flight. Typical drag coefficients range between about 0.8 and 2.0, with regular symmetric shapes tending towards the lower values. A number of drag coefficients for various shapes and flight orientations is given by Hoerner [34].

Missile penetration is examined in-depth by Clancey [15] and Baker et al. [1]. However, the equation given below is from neither of these sources, but is considered suitable for approximating penetration through building materials by fragments of less than 1 kg (this is useful here since casing fragments are generally much less than 1 kg, as indicated previously). The equation is taken from the High Pressure Safety Code [35] which suggests that a safety factor of between 1.5 and 2 should be applied to the results. It should be noted that irregular fragments may have a penetration capability only half of that calculated, whereas, pointed fragments may penetrate even further.

$$t=kM^{a}V^{b} \tag{6}$$

where t is the penetration (m), M fragment mass (kg), and V fragment velocity (m/s). The constant "k" and exponents "a" and "b" in eq. (6) vary depending on target material, as follows: Concrete (crushing strength 35 MN/m^2) 18×10^{-6}, 0.40, 1.5; Brickwork 23×10^{-6}, 0.40, 1.5; and Mild steel 6×10^{-5}, 0.33, 1.0.

Damage caused by missiles, needless to say, can vary from superficial to extensive. As a guide the Explosives Storage and Transport Committee [36] (ESTC) estimate that lethal missiles, with regards to humans, are missiles having approximately 80 J of kinetic energy. The ESTC also suggest that one fragment per 56 square metres provides individuals who are out in the open with a 1% chance of being hit. Buildings and other relatively large objects can be crushed or penetrated by missiles leading to minor hazards, such as, falling debris and glass breakage. However, impulsive loading during impact, especially from large heavy missiles, presents the greatest indirect hazard. This is because impulsive loads may instigate or encourage collapse of structures and/or escalate the amount and rate of falling debris and glass breakage. All of these missile effects may also lead to the initiation of secondary fires adding further injury. Secondary fires are discussed in Chapter 4.

The term "indirect hazard" as used above refers to all damage caused to solid media, such as, building materials and vehicles which may then present a hazard to man. It follows that "direct hazard" refers to direct injury of the human body as a result of actual physical missile contact. The majority of injuries from direct hazards relate to skin laceration and open wounds. If the velocity of the missile is sufficient and contact is made with vital organs then death may result. Experiments on skin penetration have been performed by Sperrazza and Kokinakis [37]. They have found that a relationship exists between missile mass and exposed cross-sectional area. This relationship is based on a limiting velocity (V_{50}) which corresponds to a 50% probability of skin penetration. The tests, performed with steel cubes, spheres and cylinders impacting 3 mm thick human/goat skin, assume that all missile penetration causes severe damage. Sperrazza and Kokinakis conclude that limiting velocity depends linearly on the ratio of fragment area and fragment mass, as shown by eq. (7).

$$V_{50} = k(A/M) + b \tag{7}$$

for $A/M > 0.09\ \mathrm{m^2/kg}$ and $M > 0.015$ kg, where V_{50} is the limiting velocity (m/s), A the CSA of missile along trajectory ($\mathrm{m^2}$), M the mass of fragment (kg), k is a constant (1247.1) and b is a constant (22.03).

From further work Sperrazza and Kokinakis [38] have found that skin *in situ* can be penetrated at lower impact velocities than isolated skin. The results are contrary to that expected when one considers that *in situ* fragments must traverse 10 mm of skin and subcutaneous tissue rather than 3 mm of isolated skin in laboratory tests. A number of results based on isolated skin tests are detailed in Table 9.

Other work has been performed on skin penetration. Unfortunately, direct comparisons with the findings of Sperrazza and Kokinakis are difficult to make as a result of the many differing approaches to the problem. However, Baker et al. [1] using a number of simplifying assumptions, have compared results compiled by other researchers, as shown in Fig. 4. It can be seen from Fig. 4 that the relationship estimated by Sperrazza and Kokinakis compares well with the findings of Glasstone [4], White et al. [39], Custard and Thayer [40] and Kokinakis [41]. More recently Pietersen [21] has described a relationship derived by TNO [22] relating the probability of fatality with regards to skin penetration based on fragment velocity and mass. The relationship is in the form of a probit equation, as shown below, and is applicable to fragments of less than 0.1 kg.

$$Pr = -29.15 + 2.10 \ln S \tag{8}$$

TABLE 9

Comparison of methods estimating probability of fatality from non-penetrating missile impact

Probability of fatality (%)	Fragment impact velocity (m/s)	
	Ahlers[a]	Pietersen[b]
0.5 kg fragment		
10	17	14.9
50	23	16.8
90	30	19.0
10 kg fragment		
10	8	5.0
50	11	5.6
90	13	6.3

[a] Approximate values from Ahlers [42].

[b] Approximate values from Pietersen [21].

For non-penetrating fragments between 0.1 kg and 4.5 kg: $Pr = -17.56 + 5.3 \ln S$, where $S = \frac{1}{2}MV^2$: and for non-penetrating fragments greater than 4.5 kg: $Pr = -13.19 + 10.54 \ln V$.

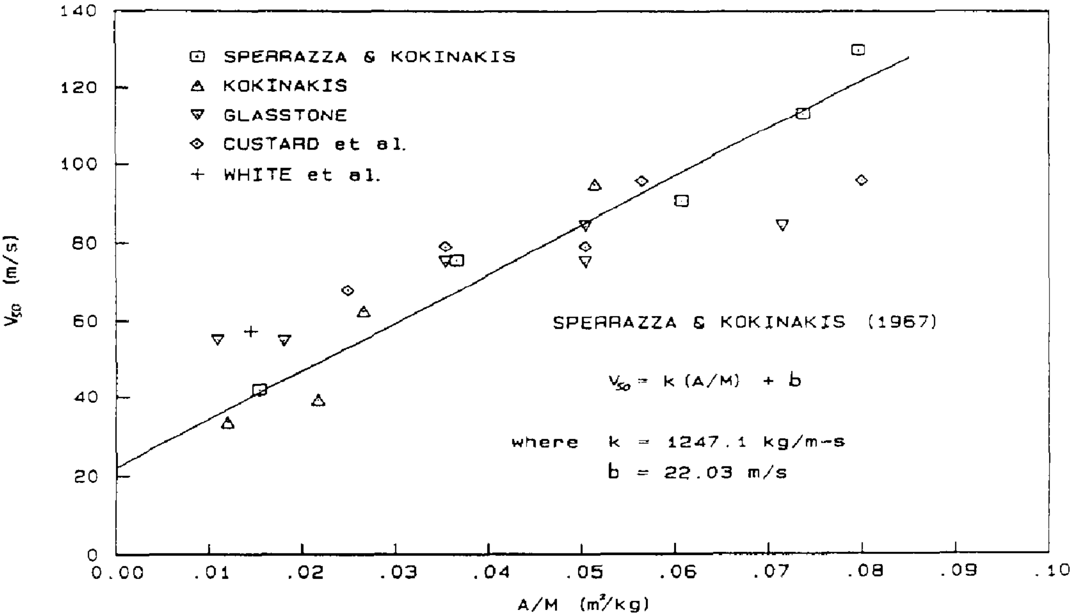

Fig. 4. Ballistic limit (V_{50}) vs. fragment area/mass for isolated human and goat skin (after [1]).

where S equals $MV^{5.115}$, in which M is the fragment mass (kg), and V fragment velocity (m/s).

Not all fragments are penetrating. Non-penetrating fragments may cause injury or death by virtue of their mass and velocity being so great that they inflict bodily translation and/or crushing effects. Such action usually results in cerebral concussion, fracture, haemorrhage and/or serve bruising of the victim. Ahlers [42] has studied the effect of non-penetrating missiles on individuals, the results of which are presented here in Fig. 5. Pietersen [21] illustrates two probit relations derived by TNO [22] for the probability of fatality from such missiles. For fragments between 0.1 kg and 4.5 kg the probit is related to kinetic energy, such that

$$Pr = -17.56 + 5.30 \ln S \tag{9}$$

where

$$S = \tfrac{1}{2}MV^2 \tag{10}$$

and M and V are as given above for skin penetration. For fragments greater than 4.5 kg the probit is related to skull fracture and given by

$$\mathrm{Pr} = -13.19 + 10.54 \ln V \tag{11}$$

where V is the fragment velocity.

Results obtained using the above probits differ from the results presented by Ahlers [42]. Given the same size fragment, compared with Ahlers, the probit

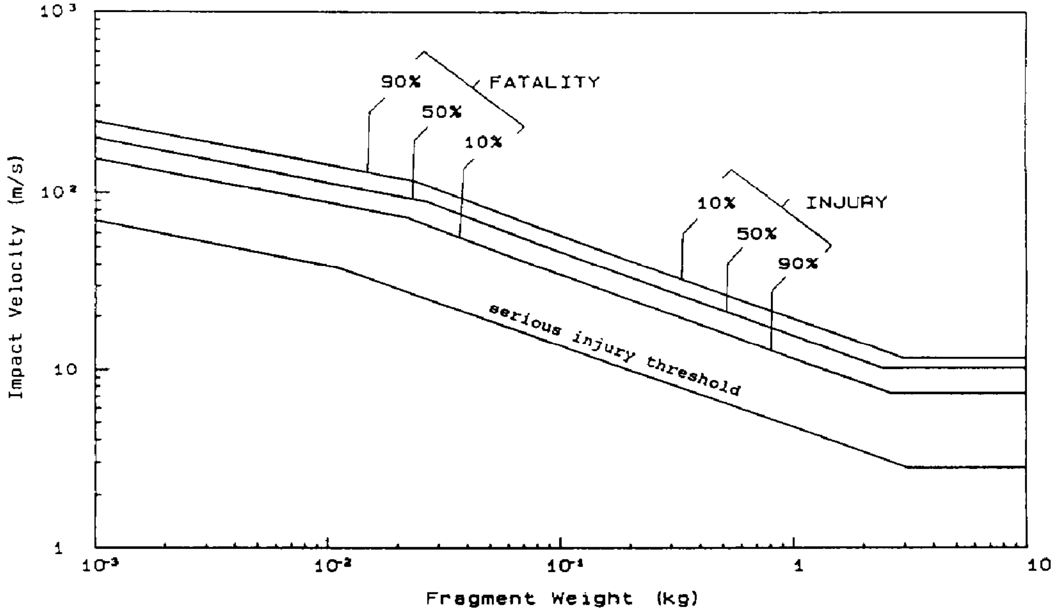

Fig. 5. Fragment impact: Human response to non-penetrating missiles (after [41]).

based on kinetic energy (i.e. fragments 0.1 kg–4.5 kg) implies that a greater impact velocity is needed to attain a specific probability of fatality. In comparison, the probit based on skull fracture (i.e. fragments >4.5 kg) implies a lower impact velocity is needed to attain a specific probability of fatality. However, there are similarities between the study conducted by Ahlers [42] and the probits presented by Pietersen [21] suggesting that they are asymptotic of a more general solution. For example, both suggest that the probability of fatality from large fragments (unlike small fragments) is related simply to impact velocity.

Further information on the effects of missile impact, with respect to humans can be gained through White [16], TNO [22], Clemedson et al. [28], Sperrazza and Kokinakis [37] and Kokinakis [41].

4. Thermal damage and injury

Extensive thermal damage from explosions is usually caused by the phenomenon of fireball growth. Fireballs cause damage as a result of igniting combustible materials and injuring humans by direct immersion and intense radiation. Thermal damage may also occur as a result of secondary fires. These fires are initiated either by instantaneous combustion of materials due to radiation exposure above material threshold levels or by missile and blast interaction with ignition sources. The number of secondary fires caused by explosion is extremely hard to quantify. For propane explosions Geffen et al. [43] have estimated the number of secondary fires as a factor of heat radiation threshold and building density. It is suggested here that a similar analogy could be employed for commercial and military explosives. Compared with fireballs, secondary fires present only a minor thermal hazard and, as such, their specific characteristics are not expanded upon here. Detailed information on secondary fires can be gained through Lees [2], Geffen [43] and Rausch et al. [44].

As previously mentioned, the major hazard from fireballs is the effect of thermal radiation damage. As a result of this most investigations into fireball characteristics have concentrated on radiant rather than conductive and convective heat transfer. However, it has been suggested by Baker et al. [1] that for small fireballs, in which less than 10 kg of substance are consumed, heat transfer by conduction and convection may play a substantial part in the heat transfer process. Regardless of this omission, for the purposes of consequence analysis, the current catalogue of research tends to support historical data collected on fireball incidents. The most authoritative work in this field is given by Rakaczky [45], with regards to munitions explosions, Gayle and Bransford [46], High [47], Bader et al. [48] and Hasegawa and Sato [49] with regards to liquid propellants and fuel explosions, and Roberts [50] with regards to releases of liquefied petroleum gas (LPG). It should be noted that much work in this field relates specifically to nuclear explosions [4]. Unfortunately the results gained on fireballs from nuclear explosions do not correspond well with data collected on fireballs resulting from chemical explosions. This disparity should be borne in mind when attempting fireball analysis. This work is chiefly concerned with commercial and conventional military explosives, and therefore the following discussion on fireball growth and damage omits any reference to nuclear explosions.

Evaluation of fireball consequences for hazard assessment requires the quantification of fireball temperature, fireball duration and fireball size. Temperature is dependent on the heat capacity of the fuel consumed and means of combustion (i.e. diffusion flame where air diffuses into the fuel or pre-mixed flame where air and fuel exist as a mixture). Fireball temperatures can vary from approximately 1350 K for flammable gases to about 5000 K for chemical explosives. It is important to note this fact when using fireball models so as to avoid erroneous conclusions. For example, High's [47] predictions for fireball size and duration are based on liquid propellants having fireball temperatures of 3600 K, whereas, Rakaczky's [45] estimates are for fuels, such as, propane, pentane and octane which have substantially lower fireball temperatures (i.e. approximately 2500 K). Similarly, Roberts [50] equations relate to propane fireballs. However, variations between fireball models are largely dependent upon the mass of substance consumed, and as such size and duration estimates may vary by as much as 50%.

As stated above, estimation of fireball size and duration varies from model to model. It is suggested by Baker et al. [1] that the results from the various models, used to estimate size and duration, are asymptotic or limiting cases of a more general solution. This claim is supported by the mathematical similarities between the models and the fact that some methods are suitable for use on fireballs consuming small quantities (i.e. less than 10 kg — Hasegawa and Sato [49]), whereas, others are best used on fireballs consuming relatively modest quantities of material (i.e. more than 20 kg — High [47] and Rakaczky [45]). However, from a review of fireball models Roberts [50] suggests that for a large range of releases (1 kg to over 100,000 kg) the following equation provides a reasonable approximation of fireball size.

$$D=5.8\,M^{1/3} \tag{12}$$

where D is the fireball diameter (m), and M the mass consumed (kg).

Similarly, Roberts suggests that for fireballs consuming less than 5 kg fireball duration is best estimated by

$$T=1.1\,M^{0.097} \tag{13}$$

and for quantities greater than 5 kg

$$T=0.83\,M^{0.316} \tag{14}$$

where T denotes the fireball duration (s), and M the mass consumed (kg).

Duration time, T, is referred to here as the period during which fireballs radiate heat. Further time-scales (of minor importance here) are those associated with duration of combustion with regards to momentum, buoyancy and deflagration and time for fireball "lift-off". These time-scales are discussed in detail by Roberts [50] together with three distinct stages of fireball development, namely:

(a) rapid growth (rapid combustion, dominated by initial momentum of release, very bright flame),
(b) little change in size (dominated by buoyancy and combustion effects, flame cooling from bright yellow to dull orange),
(c) fireball lift (rapid cooling, dominated by buoyancy effects).

The main difficulty in estimating duration stems from the absence of a discrete point as fireballs lose heat. A general consensus has not been reached on the estimation of duration and therefore large deviation is often found between fireball models. In comparison, the estimation of fireball size tends to be more consistent. This is because most hazardous materials generate fireballs which expand rapidly reaching a maximum size which is maintained for a measurable time until collapse. Rakaczky [45], in a literature review of explosions, observed that fireball size and duration can be expressed by

$$D = 3.76\,M^{0.325} \tag{15}$$

and

$$T = 0.258\,M^{0.349} \tag{16}$$

Unfortunately, no limits of applicability are given for the equations above and therefore they should be used with caution. Baker et al. [1], however, contend that Rakaczky's equations are for fireballs with temperatures approximating 2500 K. Other researchers, namely High [47] and Hasegawa and Sato [49], have evaluated similar equations, abstracted results of which are shown in Tables 10 and 11. It is suggested by Baker et al. that High's equations should

TABLE 10

Comparison of methods estimating fireball duration (after Baker et al. [1])

Mass (kg)	Time (s)			
	Rakaczky	High	Hasegawa and Sato	Roberts
1	0.26	0.30	1.07	1.10
10	0.58	0.63	1.62	1.72
10^2	1.29	1.31	2.46	3.56
10^3	2.87	2.74	3.74	7.36
10^4	6.42	5.72	5.67	15.00
10^5	14.00	12.00	8.60	32.00
10^6	32.00	25.00	13.00	65.00
10^7	79.00	52.00	20.00	135.00

TABLE 11

Comparison of methods estimating fireball size (after Baker et al. [1])

Mass (kg)	Diameter (m)			
	Rakaczky	High	Hasegawa and Sato	Roberts
1	3.76	3.86	5.25	5.80
10	7.95	8.06	11.00	13.00
10^2	17.00	17.00	22.00	27.00
10^3	36.00	35.00	46.00	58.00
10^4	75.00	74.00	95.00	125.00
10^5	159.00	154.00	195.00	269.00
10^6	335.00	321.00	402.00	580.00
10^7	708.00	671.00	828.00	1250.00

be used for liquid propellants having fireball temperatures of approximately 3600 K and where more than 20 kg of hazardous material is consumed, and that Hasegawa and Sato's equations be employed on fireballs consuming less than 10 kg.

High [47] $D=3.86\,M^{0.32}$, $T=0.299\,M^{0.32}$ (17)

Hasegawa and Sato [49] $D=5.25\,M^{0.314}$, $T=1.07\,M^{0.181}$ (18)

The models discussed above have yet to be refined so as to incorporate conductive and convective heat transfer mechanisms, which may greatly affect heat loss in small fireballs, as previously mentioned. In addition, the emissivity of fireballs has not been fully addressed. Most models assume emissivity values of between 0.7 and 1.0. However, some fireballs have extremely low "black-body" capabilities rendering the above equations inappropriate (e.g. hydrogen fireballs).

Fireball size and duration is summarised in Table 12.

Fireball consequence analysis takes the form of estimating thermal radiant heat flux and, subsequently, radiated thermal energy. The treatment and derivation of these parameters are complex and for the purposes of this paper need no full description. A suitable explanation is given by High [33] and Baker et al. [1]. It is sufficient here to note that the analysis is based on fireball size, temperature and duration. On the assumption that fireball size and temperature remain constant High derives the following equations for radiant heat flux, q, and radiated energy per unit area, Q.

$$(q/o^4)=(GD^2/R^2)/(F+D^2/R^2) \tag{19}$$

$$Q/(bGM^{1/3}o^{2/3})=(D^2/R^2)/(F+D^2/R^2) \tag{20}$$

where q is the heat flux (J/m²s—i.e. W/m²), Q the radiated energy (J/m²), D the diameter of fireball (m), o the temperature of fireball (k), R the distance to

TABLE 12

Fireball size, D, and duration, T, parameters from $D=AM^B$ and $T=AM^B$

Model	Diameter (m)		Duration (s)	
	A	B	A	B
High[a]	3.86	0.320	0.299	0.320
Hasegawa and Sato[b]	5.25	0.314	1.070	0.258
Rakaczky[c]	3.76	0.325	0.258	0.349
Roberts[d]	5.8	0.333	0.830	0.316
Roberts[e]	–	–	1.100	0.097

[a] High [47] – liquid propellants and fuel explosions, fireball temperatures approx. 3600 K, greater than 20 kg.

[b] Hasegawa and Sato [49] – liquid propellants and fuel explosions, less than 10 kg.

[c] Rakaczky [45] – munition explosions, fireball temperatures approx. 2500 K.

[d] Roberts [50] – propane, 1 kg to over 100,000 kg.

[e] Roberts [50] – propane, less than 5 kg.

fireball (stand-off distance) (m), M the consumed mass (kg), F a transmission coefficient (161.7), G a transmission coefficient (5.26×10^{-5}), and bG the transmission product (2.04×10^4).

Both equations above are based on static fireball diameters. High [33] (employing a time variant analogy) has shown that equations can be derived to allow for fireball growth. However, these are not expanded upon here since they add little to the assessment of fireball damage.

Radiated heat, E, is given by Roberts [50] as

$$E=FMQ/T \tag{21}$$

where E denotes a radiated heat (kW), F a fraction of total heat released (0.2–0.4), M a mass consumed (kg), Q a heat of combustion (kJ/kg), and T a fireball duration (s) (where $T=0.45\,M^{1/3}$).

From the above the intensity of heat radiation on a target perpendicular to the direction of radiation (i.e. heat flux) is given by

$$I=E/4\pi L^2 \tag{22}$$

where I is the intensity of heat radiation (kW/m^2) (note; "I" is referred to as "q" in the equations given by High [33]), E the radiated heat (kW) and L a distance from centre of fireball to target (m).

The effect of fire on buildings can be related directly to the intensity of radiated heat (i.e. heat flux). Most research has concentrated on the ignition of wood [1, 51]. Lawson and Simms [51] estimate spontaneous ignition of wood from the following equation.

$$(q-q_s)t^{4/5}=k \tag{23}$$

where q is the heat flux (W/m^2), q_s the critical heat flux for spontaneous ignition (25,400 W/m^2), t the duration of heat flux (s), and k is a constant (6730).

The equation given above is based on empirical data and is a general relationship for all types of wood. The critical radiation intensity (i.e. heat flux) to cause spontaneous ignition of wood is given as 25.4 kW/m^2. Other relationships for differing materials exist. However, the vast majority refer to nuclear explosions which are not strictly comparable with chemical explosions, as previously explained. For further information reference should be made to Glasstone and Dolan [4] and Baker et al. [1].

Damage to the human body from thermal radiation may result in death or injury from severe burns. Injury caused by radiation can be quantified by temporary or permanent loss of sight. Miller and White [52] have derived relationships linking heat flux and choriorentinal burns with respect to time. However, thermal radiation injury is more commonly based on the burning of bare skin [1, 13, 53]. Buettner [53] estimates human pain with respect to heat flux. Figure 6 illustrates the relationship derived by Buettner with respect to heat flux for non-nuclear fires. The two lines shown provide a split between bearable and unbearable pain (second degree burns). Unbearable pain is said to occur [53] when a temperature of 44.8 °C is exceeded at a skin depth of 0.1 mm. Exceeding such a temperature rapidly increases the victim's pain. The pain then gradually fades indicating that total skin irradiation has occurred. It is stated by Hymes [54] that for each increase of 1°C above the threshold the rate of injury is trebled. For example, compared with the threshold the damage rate is roughly 100 times greater at 50 °C.

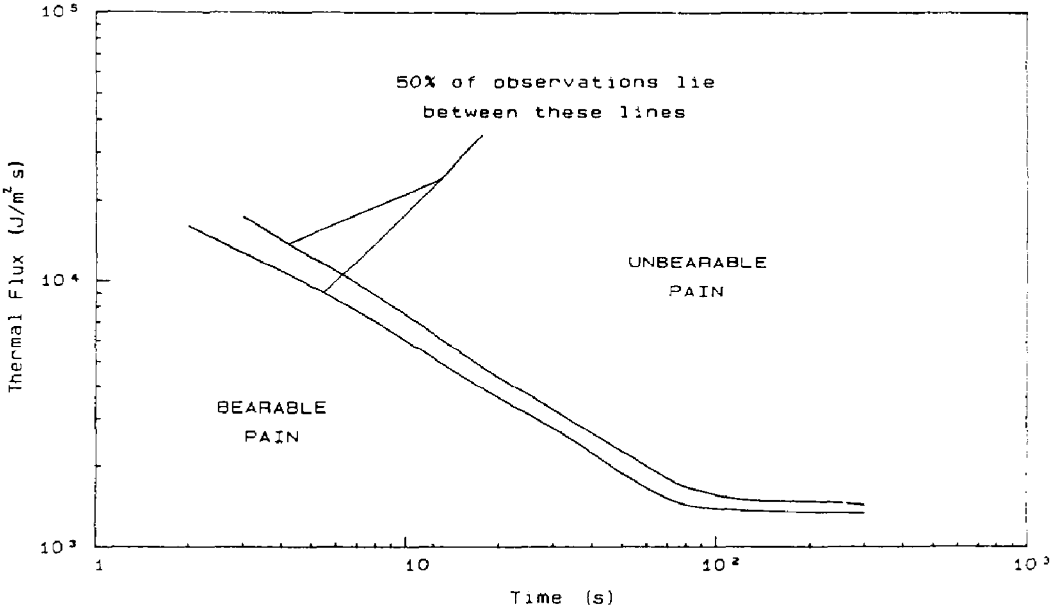

Fig. 6. Threshold of pain from thermal radiation on bare skin (after [58]).

The probability of death from second degree burns has been estimated by the US Department of the Army [55]. They derive a plot of the probability of fatality vs. the percentage of second degree burns, as shown in Fig. 7. Exposed skin varies from season to season but is estimated to average [43] about 27%. This estimate of skin exposure approximates to the exposure of the head and both arms. Thus, from Fig. 7 it can be seen that the probability of fatality from second degree burns for average skin exposure is about 10%.

A detailed review of the physiological and pathological effects of thermal radiation is given by Hymes [54] together with new information. It is broadly concluded that those exposed to heat fluxes capable of inflicting third degree burns within 10 seconds are unlikely to survive. Precise probabilities of injury and survival are difficult to gauge. The effects of radiation burns are related to burnt surface area, depth of burn, age of recipient and clothing characteristics, etc. All of these factors are discussed by Hymes [54].

Probability of death with respect to the proportion of body surface area burnt is given by Pietersen [21] and reproduced here in Table 13. As a "rule of thumb" it is suggested by Hymes [54] that for 15% burnt surface area (adult, head and hands) and injury no worse than second degree-plus all healthy adults under 50 can be expected to survive, whereas, 50% of those over 60 can be expected to die. Compared with adults the proportion of infants surviving is somewhat lower. This is due to the greater surface area exposed (i.e. head and hands approximate 30% of infant area) and the greater medical attention required. The approximate distribution of adult surface area (skin) is given in Table 14.

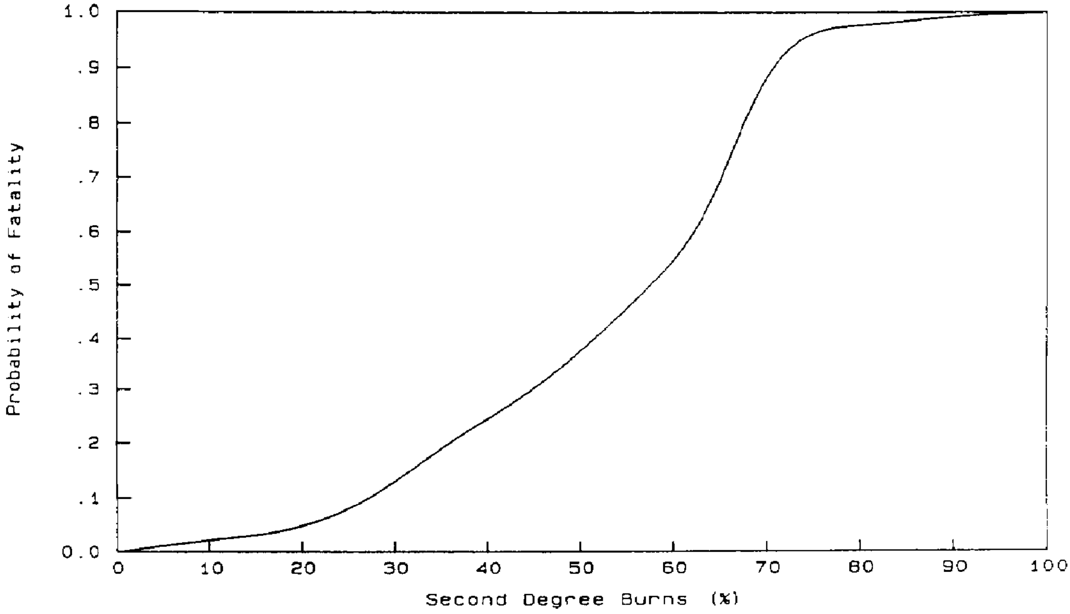

Fig. 7. Fatality criterion: Second degree burns (after [54]).

TABLE 13

Relation between age, proportion of body surface area burnt and mortality rate (after Pietersen [21])

Body area burnt (%)	Age (years)																
	0–4	5–9	10–14	15–19	20–24	25–29	30–34	35–39	40–44	45–49	50–54	55–59	60–64	65–66	70–74	75–79	80+
93+	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
88–92	0.9	0.9	0.9	0.9	1	1	1	1	1	1	1	1	1	1	1	1	1
83–87	0.9	0.9	0.9	0.9	0.9	0.9	1	1	1	1	1	1	1	1	1	1	1
78–82	0.8	0.8	0.8	0.8	0.9	0.9	0.9	1	1	1	1	1	1	1	1	1	1
73–77	0.7	0.7	0.8	0.8	0.8	0.8	0.9	0.9	0.9	1	1	1	1	1	1	1	1
68–72	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.8	0.9	0.9	0.9	1	1	1	1	1	1
63–67	0.5	0.5	0.6	0.6	0.6	0.7	0.7	0.8	0.8	0.9	0.9	1	1	1	1	1	1
58–62	0.4	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.9	1	1	1	1	1
53–57	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.7	0.8	0.9	1	1	1	1	1
48–52	0.2	0.2	0.3	0.3	0.3	0.3	0.4	0.5	0.6	0.6	0.7	0.8	0.9	1	1	1	1
43–47	0.2	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.6	0.7	0.8	1	1	1	1
38–42	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.4	0.5	0.6	0.8	0.9	1	1	1
33–37	0.1	0	0	0	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.7	0.8	0.9	1	1
28–32	0	0	0	0	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.4	0.6	0.7	0.9	1	1
23–27	0	0	0	0	0	0	0.1	0.1	0.1	0.2	0.2	0.3	0.4	0.6	0.7	0.9	1
18–22	0	0	0	0	0	0	0	0.1	0.1	0.1	0.1	0.2	0.3	0.5	0.6	0.8	0.9
13–17	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0.2	0.3	0.5	0.6	0.7
8–12	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0.2	0.3	0.5	0.5
3–7	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.2	0.3	0.4
0–2	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.2	0.2

TABLE 14

Distribution of skin surface area

Body part	Proportion (%)
Head	7
Trunk	35
Arms	14
Hands	5
Thighs	19
Legs	13
Feet	7

From a number of empirical relations [13,56], and based on an average population, Pietersen [21] derives probits relating burns and death (an average population is not defined). The probits assume approximately 20% exposed surface area. Severity of injury is categorised by the depth of skin to which a temperature difference of 9 K occurs, such that

$$\begin{array}{ll} \text{1st degree burns} & <0.12\text{ mm skin penetration} \\ \text{2nd degree burns} & <2\text{ mm skin penetration} \\ \text{3rd degree burns} & >2\text{ mm skin penetration} \end{array} \tag{24}$$

The probits given by Pietersen are as follows.

$$\begin{array}{ll} Pr=-39.83+3.0186\ln(tq^{4/3}) & \text{1st degree burns} \\ Pr=-43.14+3.0188\ln(tq^{4/3}) & \text{2nd degree burns} \\ Pr=-36.38+2.56\ln(tq^{4/3}) & \text{lethality (death)} \end{array} \tag{25}$$

where Pr is the probit, t the exposure time (s) and q the heat of radiation (kW/m^2).

For completeness, certain radiation threshold levels and effects are detailed here in Tables 15, 16 and 17.

Finally, it should be noted that transient and steady state fires (for both materials and humans) require differing magnitudes of heat flux for specific levels of damage. For example, first degree burns from secondary fires (steady state fires) are likely from heat fluxes approaching 4.5 kW/m^2 (after 20 s), whereas, similar damage from fireballs (transient fires) can be expected at 125 kJ/m^2. It should be noted that due to the short duration of fireballs total radiated heat is used to estimate damage levels. Tables 15 and 16, which are reproduced in-part from the Rijnmond Public Authority Study [57] into the hazards from a number of chemical installations, serve to illustrate these points.

TABLE 15

Radiation intensity damage: Steady state fires (after Rijnmond Public Authority [57])

Heat flux (kW/m^2)	Effect
37.5	Damage to industrial equipment
25.0	Minimum energy required to ignite wood at infinitely long exposure
4.5	Sufficient to cause pain to personnel if unable to reach cover within 20 s, 1st degree burns likely
1.6	No discomfort to long exposure

TABLE 16

Radiation intensity damage: Transient fires (after Rijnmond Public Authority [57])

Heat flux (kJ/m^2)	Effect
375	3rd Degree burns
250	2nd Degree burns
125	1st Degree burns
65	Threshold of pain, no reddening or blistering of skin

TABLE 17

Pain and blister thresholds with respect to heat radiation intensity and time[a]

Heat flux (kW/m^2)	Time (s)	
	Pain	Blister
3.7*	20.0	–
4.2	13.5	33.8
5.2	10.1	–
6.2*	10.0	–
6.3	7.8	20.8
8.4	5.5	13.4
9.7*	5.0	–
12.6	2.9	7.8
16.8	2.2	5.6
18.0*	2.0	–

[a] Time to threshold of pain, data from Stoll and Greene [58], except time to unbearable pain.
* Data from Buettner [59].

5. Aggregated consequence models

As can be inferred from the information and data presented in this paper, the evaluation of explosion effects is often detailed and prone to inaccuracy. Estimating the number of casualties and extent of building damage is hindered by a multitude of factors, namely

(a) mass of explosive consumed,
(b) distance from source to target,
(c) blast duration,
(d) terrain,
(e) exposure,
(f) fragment generation, velocity, range and projectory,
(g) heat intensity,
(h) structural and material building characteristics.

Furthermore, it is difficult to distinguish between fatalities simply caused by overpressure effects, bodily translation and missile impact. Other causes of death which are hard to distinguish include asphyxia following burial, carbon monoxide poisoning and chronic illness aggravated by shock. In addition to these problems the majority of urban populations will be indoors during an explosion. Only a limited amount of research has been conducted on the effects of explosion with regards to "indoor" populations. The U.S. Department of Transportation [44] have attempted to produce credible methodologies in order to quantify indoor population damage. However, "indoor" and "outdoor" environments are not easily related and no simple scaling laws or means of extrapolating external blast damage to internal blast damage are available. Consequently, the assessment of damage to indoor populations is limited and the accuracy of results poor.

As a consequence of the differences between indoor and outdoor environments, and as a result of the problems outlined above, there are very few simple aggregated consequence models which are useful in estimating damage and casualties from explosion. A number of models have been developed for vapour cloud explosions but very few for those explosions of interest here (i.e. condensed explosions from the accidental initiation of commercial/military explosives). It is apparent from those concerned with explosives safety, that a simple and accurate means of estimating damage and casualties from condensed explosions would be very useful. It is thought here that the best means of achieving this is by the analysis of historical events to produce empirical methods of evaluation. Workers at the University of Technology, Loughborough [60], have adopted this approach and produced a model suitable for the assessment of condensed explosions occurring without warning in built-up areas.

The consequence model developed at Loughborough by Withers and Lees [60] is applicable only to those explosives which have a mass explosion hazard (i.e. UN hazard division 1.1 explosives). Fatalities are estimated from data collected on historical events and empirical data collected on the effects of blast overpressure. Historical events include World War II bombings, chemical explosions, domestic gas explosions and a number of natural disasters such as earthquakes and tornadoes. Empirical data consist primarily of relationships linking injury and blast overpressure. Due to the difficulties encountered in estimating fatalities cause of death is split into primary and secondary types. Primary deaths are classed as those which occur in the near field and are entirely due to overpressure. The likelihood of death from overpressure is related to impulse and duration. In comparison, secondary deaths are related to housing damage, specifically the number of dwellings made uninhabitable. For every 10 dwellings made uninhabitable one secondary death is assumed. Both primary and secondary deaths are related to distance and mass of explosive consumed and hence are categorised by primary and secondary radii. Individuals who survive within the radii are balanced by those who survive outside the radii. The explosion consequence model is detailed here in Figs. 8 and 9.

The explosion effects model developed at Loughborough [60] suffers from one or two omissions, namely the absence of deaths resulting from casing/packaging fragments and deaths from primary and secondary fires. However, the model estimates well the number of fatalities from a number of historical incidents. Of particular interest is the estimate of fatalities from low yield explosions. The model approximates favourably fatalities from V-2 rocket/bombing raids and other similar sized explosions (0.5 tonne–2 tonne).

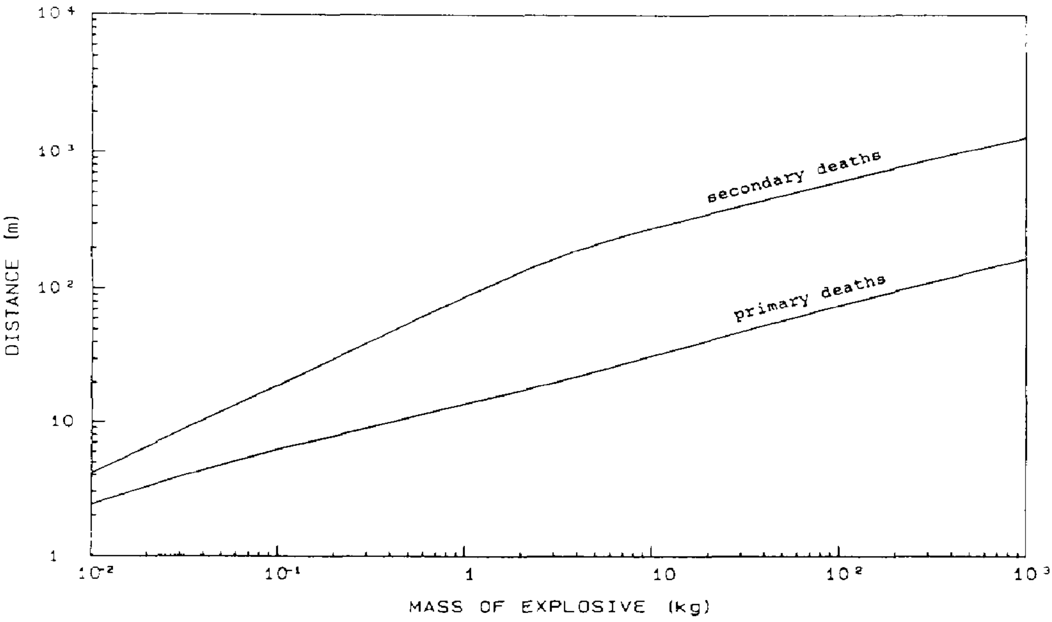

Fig. 8. Primary and secondary causes of death for man: Mass of explosive and distance for 50% mortality (after [59]).

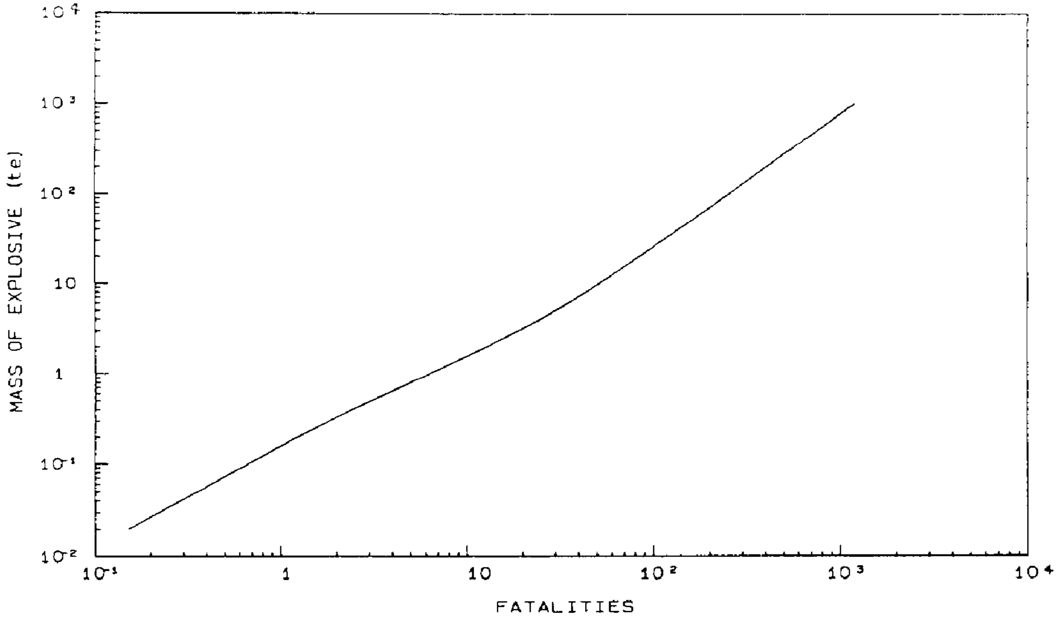

Fig. 9. Model for fatalities resulting from an explosion of a condensed phase explosive in a built-up area (Basis 4000 persons/km^2, 2.5 persons/house [59]).

Regardless of any shortcomings, the author has found no similar "complete" explosion effects models. The model appears to be unique and at present the only one available for the estimation of fatalities from condensed explosions occurring without warning in built-up areas.

Acknowledgements

This paper is based in part on a thesis submitted by the author to the Loughborough University of Technology for the degree of Ph.D., entitled "A Methodology for the Quantitative Risk Assessment of the Road and Rail Transport of Explosives". The thesis took much of its inspiration from a study conducted by the author and Professor F.P. Lees of the Loughborough University of Technology into the hazard of transporting military explosives by road and rail.

The work contained herein relates to those substances and articles designed and manufactured so as to provide an explosion or explosive effect (i.e. largely conventional commercial and military explosives).

References

1 W.E. Baker, P.A. Cox, P.S. Westine, J.J. Kulesz and R.A. Strehlow, Explosion Hazards and Evaluation, Elsevier, Amsterdam, 1983.

2 F.P. Lees, Loss Prevention in the Process Industries, Butterworths, London, 1980.

3 G.F. Kinney, Explosives Shocks in Air, MacMillan, New York, 1962; G.F. Kinney and K.J. Graham, Explosives Shocks in Air, Springer-Verlag, New York, 1985.

4 S. Glasstone and P.J. Dolan, The Effects of Nuclear Weapons, 3rd edn., U.S. Department of Defence and U.S. Department of Energy, 1977.

5 N.F. Scilly and W.G. High, The blast effects of explosions, in: Proc. Fifth Int. Symp. on Loss Prevention and Safety Promotion, Cannes, 1986.

6 C.S. Robinson, Explosions, Their Anatomy and Destructiveness, McGraw-Hill, New York, 1944.

7 D.E. Jarrett, Derivation of the British safety distances, Ann. New York Acad. Sci. 152(1), (1968) 18–35.

8 R. Assheton, The History of Explosions, The Institute of Makers of Explosives, Wilmington, DE, 1930.

9 W.E. Baker, Explosions in Air, University of Texas Press, Austin, TX, 1973.

10 J.H. Turnbull and K. Walter, Explosions in Air and Water, Chemical Systems Group, Royal Military College of Science, Shrivenham, Wiltshire, 1982.

11 W.C. Brasie and D.W. Simpson, Guidelines for estimating damage from chemical explosions. Presented at the Symp. on Loss Prevention in the Process Industries, 63rd Natl. Meeting, St. Louis, MO, 18–21 February, 1968, Reprint 21A

12 D.R. Stull, Fundamentals of Fire and Explosion, AIChE Monograph Ser., 73 (1977) 10.

13 N.A. Eisenberg, et al., Vulnerability Model. A simulation system for assessing damage resulting from marine spills. National Technical Information Service Report AD-A015-245, Springfield, VA, 1975.

14 L.E. Fugelso, L.M. Weiner and T.H. Schiffman, Explosion effects computation aids. General American Transportation Co., Gen. American Research Division, GARD Prog. 1540 AD903279, Niles, IL, 1972.

15 V.J. Clancey, Diagnostic features of explosion damage, in: Proc. Sixth Int. Meeting of Forensic Sciences, Edinburgh, 1972.

16 C.S. White, The scope of blast and shock biology and problem areas in relating physical and biological parameters, Ann. New York Acad. Sci., 152(1) (1968) 89–102.

17 A.E. Hirsch, The tolerance of man to impact, Ann. New York Acad. Sci. 152(1) (1968) 168–171.

18 A.J. Vadala, Effects of gun explosions on the ear and hearing mechanism, Military Surgeon, 66 (1930) 710–822.

19 G.A. Henry, Blast injuries of the ear, Laryngoscope, 55 (1945) 663–672.

20 Reider (1968). (see reference 4, page 595).

21 C.M. Pietersen, Consequences of accidental release of hazardous material, J. Loss Prev. Process Ind., 3 (1990) 136–141.

22 TNO, Department of Industrial Safety, P.O. Box 342, 7300 AH Apeldoorn, The Netherlands.

23 Lovelace Foundation for Medical Education and Research, Albuquerque, NM.

24 J.G. Bowen, et al., Estimate of man's tolerance to the direct effects of air blast. DASA 2113, Lovelace Foundation for Medical Education and Research, Albuquerque, NM, 1968.

25 E.R. Fletcher and I.G. Bowen, Blast-induced translation effects. Ann. New York Acad. Sci. 152(1) (1968) 378–403.

26 F.G. Hirsch, Effects of overpressure on the ear — A review, Ann. New York Acad. Sci. 152(1) (1968) 147–162.

27 W.E. Baker and G.A. Oldham, Estimates of blowdown of quasi-static pressures in vented chambers. Edgewood Arsenal, Contractor Report EM-CR-76029, Report No. 2, 1975.

28 C.J. Clemedson, G. Hellstrom and S. Lingren, The relative tolerance of the head, thorax and abdomen to blunt trauma, Ann. New York Acad. Sci., 152(1), (1968) 187.

29 A. Longinow et al., People survivability in a direct effects environment and related topics. Project No. J6144, AD 764114, IIT Research Institute, May 1973.

30 P.L. Holden and A.B. Reeves, Fragment hazards from failures of pressurised liquefied gas vessels, in: The Assessment and Control of Major Hazards, Institute of Chemical Engineers, 1985, p. 205.

31 T.A. Zaker, Computer program for predicting casualties and damage from accidental explosions. Technical Paper No. 11, Department of Defence Explosives Safety Board, AD-A012847, May 1975.

32 T.A. Zaker, Fragment and debris hazard, Technical Paper No. 12, Department of Defence Explosives Safety Board, AD-A013634, July 1975.

33 W.G. High, Explosions: Occurrence, containment and effects. Loughborough University of Technology, Department of Chemical Engineering, Course on Loss Prevention in the Process Industries, 1976.

34 S.F. Hoerner, Fluid-Dynamic Drag, Published by the author, Midland Park, NJ, 1958.

35 B.G. Cox and G. Saville, High Pressure Safety Code. Imperial College: High Pressure Technology Association, London, 1975.

36 Safety Services Organisation, Procurement Executive, Explosives Training Course. Royal Military College of Science, Shrivenham, Wiltshire, 19–22 June, 1989.

37 J. Sperrazza and W. Kokinakis, Ballistic limits of tissue and clothing. Technical Note No. 1645, U.S. Army Ballistic Research Laboratory, RDT&E Project No. 1PO 256 01A 027, January 1967.

38 J. Sperrazza and W. Kokinakis, Ballistic limits of tissue and clothing, Ann. New York Acad. Sci, 152(1) (1968) 163–167.

39 C.S. White et al., Comparative nuclear effect of biomedical interest. CEX-58.8, Civil Effects Study, U.S. Atomic Energy Commission, January 1961.

40 G.H. Custard and J.R. Thayer, Evaluation of explosive storage safety criteria. Falcon Research and Development Company, Contract DAHC 04-69-C-0095, March 1970.

41 W. Kokinakis, A new methodology for wounding and safety criteria. Proc. of the 16th Explosives Safety Seminar, September 1974, pp. 1209–1226.

42 E.B. Ahlers, Fragment hazard study. Minutes of the 11th Explosives Safety Seminar, Memphis, TN, September 1969.

43 C.A. Geffen, Assessment of the risks of transporting propane by truck and train. Battelle Pacific Northwest Laboratory, Report PNL 3308, Richland, WA, March 1968.

44 A.H. Rausch, N.A. Eisenberg and C.J. Lynch, Continuing development of the vulnerability model — Final report. National Technical Information Service Report AD-AO-044197, Springfield, VA, 1977.

45 J.A. Rakaczky, The suppression of thermal hazards from explosions of munitions: A literature survey. BRL Interim Memo. Report No. 377, Aberdeen Proving Ground, MD, May 1975.

46 J.B. Gayle and J.W. Bransford, Size and duration of fireballs from propellant explosions. NASA TM X-53314, George C. Marshal Space Flight Center, Huntsville, AL, August 1975.

47 R.W. High, The saturn fireball, Ann. New York Acad. Sci. 152(1) (1968) 441–451.

48 B.E. Bader, A.B. Donaldson and H.C. Hardee, Liquid-propellant rocket abort fire model, J. Spacecraft, 8(12) (1971) 1216–1219.

49 K. Hasegawa and K. Sato, Experimental investigation of the unconfined vapour-cloud explosions of hydrocarbons. Technical Memo. of Fire Research Inst., No. 12, Fire Defence Agency, Japan, 1978.

50 A.F. Roberts, Thermal radiation hazards from releases of LPG from pressurised storage, Fire Saf. J., 4 (1981/1982) 197–212.

51 D.I. Lawson and D.L. Simms, The ignition of wood by radiation, Br. J. Appl. Phys., 3 (1952) 288.

52 Miller and White. (See reference 4, p. 551).

53 K. Buettner, Effects of extreme heat on man, J. Am. Med. Assoc. 144 (1950) 732–738.

54 I. Hymes, The Physiological and Pathological Effects of Thermal Radiation. SRD R 275. Safety and Reliability Directorate, United Kingdom Atomic Energy Authority, Wigshaw Lane, Culcheth, Warrington, September 1983.

55 U.S. Department of the Army, Nuclear Handbook for Medical Service Personnel, TM-8-215. April 1969.

56 C.M. Pietersen, Analysis of the LPG-incident in San Juan Ixhuasapec, Mexico City, 19 November 1984. TNO report. TNO, Department of Industrial Safety, P.O. Box 342, 7300 AH Apeldoorn, The Netherlands, 1985.

57 Risk Analysis of Six Potentially Hazardous Industrial Objects in the Rijnmond Area, A Pilot Study. A report to the Rijnmond Public Authority, D. Reidel, Dordrecht, 1982.

58 A.M. Stoll and L.C. Greene, Relationship between pain and tissue damage due to thermal radiation, J. Appl. Physiol. 14 (1959) 373.

59 K. Buettner, Effects of extreme heat and cold on human skin. II. Surface temperature, pain and heat conductivity in experiments with radiant heat, J. Appl. Physiol., 3 (1951) 703.

60 R.M.J. Withers and F.P. Lees, The assessment of major hazards: The lethal effects of a condensed phase explosion in a built-up area. LUT, MHC/86/3., Department of Chemical Engineering, Loughborough University of Technology, Loughborough, 1986.