

THE ASSESSMENT OF MAJOR HAZARDS: THE LETHAL EFFECTS OF A  
CONDENSED PHASE EXPLOSION IN A BUILT-UP AREA

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For installations handling explosive materials there is a requirement for the purposes of hazard assessment for methods which give an estimate of the lethality of an explosion in a built-up area. A model for the lethal effects of a condensed phase explosion is derived, based on a simplified classification of explosion fatalities into primary and secondary deaths. Primary deaths occur almost entirely in the near field and are due to the direct effects of the blast, secondary deaths occur in both near and far fields and are associated with building damage. The model consists of correlations for primary and secondary deaths as a function of mass of explosive and distance. The application of the model to vapour cloud explosions is briefly discussed.

INTRODUCTION

The assessment of a major explosion hazard involves the determination of the effects of the explosion on people. There are available some data on the effects on people in the open for some particular injury modes, including eardrum rupture, lung haemorrhage, bodily translation, missile impact and so on, but these are of limited use without guidance on their use to determine the overall mortality. Moreover, in most accident situations the majority of people will be indoors, but again there is little information available in usable form on the effects of explosion on people in buildings.

The approach adopted here is to combine the use of experimental work on the effect of blast on animals and historical data on injury associated with housing damage. In the near field a relation is derived for primary causes of death arising from the direct effects of blast, while in the near and far fields a relation for secondary causes is based on the correlation of fatalities with housing damage. The paper gives a model for the lethality of explosions in built-up areas based on these primary and secondary causes of death.

The model is intended primarily for the assessment of the hazard of an explosion which occurs in the open. It is applicable to condensed phase explosions only. The same general approach may be applicable to vapour cloud explosions also, but this aspect, though briefly discussed, is beyond the scope of the paper.

The variability between individual explosions of the same nominal energy, both in respect of the overpressures measured and the casualties and damage caused, is well known. It is emphasized, therefore, that the model derived is intended for the estimation of average effects.

## BACKGROUND

As a result of the development of aerial bombing of civilian populations during the Second World War investigations of the effectiveness of bombs were undertaken by both sides. Since the war further extensive studies have been carried out with particular reference to the effects of nuclear weapons.

In the UK Professor Zuckerman played a leading role in work sponsored by the Ministry of Home Security in 1939-41 and wrote a number of papers (1-3). He was involved both in air raid casualty surveys and in experiments in which animals were exposed to the effects of blast. The Germans also did work on blast effects (4).

In the US during the 1960s and 1970s a large programme of research was carried out at the Lovelace Foundation on the effects of blast on animals and on the application of the results obtained to man with particular reference to nuclear weapons (5-9).

The behaviour of blast waves has also been extensively studied. For condensed phase explosives, i.e. high explosives such as TNT, correlations are available for the estimation of the blast wave characteristics as function of the mass of explosive (e.g. Baker *et al* (10)). Other relations are available which correlate housing damage with mass of explosive (11,12).

### Blast Wave Characteristics

The characteristics of the blast wave from the explosion of a condensed phase explosive such as TNT have been the subject of a number of studies, of which reference may be made to some of those most frequently quoted (13-23). A full account is given by Baker *et al* (10).

The blast wave parameters such as overpressure, impulse and duration time are correlated, using scaling laws, in terms of scaled distance. There are a number of correlations which give broadly similar results. The overpressure correlations show a degree of experimental scatter. A plot showing the results obtained by various workers is given in Baker *et al* (their Figure 2-3).

The usual relation is for free air explosions. For an explosion at ground level it is necessary to multiply the actual mass of explosive by a factor which takes account of the reflection of the blast by the ground. For an explosion in which no crater is formed the factor is 2, but for a condensed phase explosive the factor recommended is 1.8, which allows for crater formation. A factor of 1.8 has been used here. Figure 1 shows the overpressure from a condensed phase explosion as a function of mass of explosive and distance. It has been calculated from the correlations referred to and using the reflection factor of 1.8 just mentioned.

For small charges and duration times use has also been made of the data on blast wave parameters given by Zuckerman (2) for his experiments. Data given by Desaga (4) and by Kingery and Pannill (19) have been used as a crosscheck.

The account of blast effects given below is principally in terms of peak overpressure. The peak reflected pressure is a function both of the peak overpressure and the peak dynamic pressure, which are directly related. The latter is dominant in the near field and the former in the far field.

### Casualties in Air Raids

In his work on air raid casualties Zuckerman found that as far as lung damage was concerned it was difficult to distinguish between the effect of the blast wave pressing on the body and that of body translation or impact of missiles on the body. He concluded that fatal casualties which

showed little or no external sign of injury would probably only in rare cases have died from the direct effects of blast. Other causes of death in such circumstances are asphyxia following burial, carbon monoxide poisoning and chronic illness aggravated by shock.

Zuckerman pointed out that the overpressure necessary to bowl a person over is only slightly less than that likely to affect the internal organs and that when a person is violently thrown against a hard surface, injuries may occur to internal organs which are difficult to distinguish from those which might have occurred due to the direct blast pressure.

#### Casualties in Chemical and Gas Explosions

A study of 81 chemical and gas accidents has been made by Settles (23). Of these, 44 involved fire and explosion, 23 fire only and 14 a detonation reaction. Settles states:

"The 14 accidents in which detonating forces were present resulted in injuries to 35 persons and 34 fatalities. It appears from information available that only one of these 34 deaths resulted from blast overpressures that are associated with a detonating reaction. However, this one fatality was not the result of blast damage to human tissue. Rather, the blast pressure caused this individual to be propelled as a projectile. The other 33 persons who died in these 14 accidents were located at points where the density of flying fragments, and in some cases, the lethal searing of radiant heat were so great that their deaths were certain, even though there had been no blast effects".

It may be noted that although these incidents are presumably typical of industrial explosions, they differ from some other explosions considered in this paper in that there is normally a separation zone between an industrial site and any housing, so that in so far as the nature of the casualties changes with distance, those just quoted may be somewhat different from those which apply to an explosion occurring at random in a built-up area.

#### Casualty Classifications

From the examination of air raid casualties Zuckerman (2) derived the classification of casualties shown in Table 1.

In the Lovelace Foundation work two modes of injury which were extensively investigated were those due to

- 1) The overpressure of the blast wave on the body
- 2) The translation of the body by the blast wave.

The first of these acts on the lungs so as to cause lung haemorrhage, the second causes injury by decelerative tumbling with flailing of the limbs and/or impact with hard objects.

In an accidental explosion in a built-up area the casualties will fall into two main categories: those in the near field caused by the direct effects of the blast wave (overpressure, translation) and those in both the near and far fields caused by building damage. For the purposes of the assessment of the hazard of such explosions an alternative classification of casualties is therefore proposed, consisting of just two categories, primary and secondary casualties. The primary casualties correspond broadly to Zuckerman's categories 1 and 2 and the secondary category to his category 3. His category 4 refers to fire rather than explosion and is not considered here. The modes of injury mentioned as those principally investigated by the American workers are both in the primary category.

### RADIUS FOR DEFINED DEGREE OF INJURY OR DAMAGE

In hazard assessment use is often made of the radius at which there is a 50% probability of a defined effect, usually injury or damage. This is referred to here as the radius for 50% effect, or  $R_{50}$ . Use is also made of the radius of the circle such that the number of targets inside the circle which do not suffer the effect is balanced by the number outside which do. This is referred to here as the radius of the 100% effect circle, or  $R_{100}$ . Conceptually, these two radii are quite distinct. In practice they will often have similar numerical values. They converge where the intensity of the physical phenomenon decays rapidly and where its effect on the target passes through a narrow zone from zero to 100% effect. A quantitative treatment has been given by Lees *et al* (24).

### DENSITY AND OTHER CHARACTERISTICS OF EXPOSED POPULATION

The casualties to be expected will be a function of the population exposed. An account of the density and other characteristics of the exposed population around a major hazard site has been given by Petts *et al* (25). The model described below includes population density or, in other words, housing density and occupancy, as one of its parameters.

### PRIMARY CAUSES OF DEATH

#### Death By Overpressure On Body

Zuckerman carried out experiments in which tethered animals (goats, rabbits, rats, etc.) were exposed to blast from bombs. Most of the work was done using 70 lb bombs in paper containers, so as to avoid the effects of fragments, but some work was done with 500 lb GP bombs. The main aim of the work was to establish the parameters of the blast mechanism as a direct cause of death with special reference to the specification of shelters for use in air raids. Some of the experiments involved the protection of the animals' bodies in cases so that only the head and breathing passages were exposed.

Zuckerman states that when a bomb detonates the pressure generated within the casing is of the order of 100 to 650 tons per square inch. The bursting of the bomb gives rise to a blast wave which for a 70 lb charge at 30 ft gives an overpressure of about 15 psi and a duration time of about 5 ms.

He describes the experiments as follows (1):

"The closest an animal was placed to the charge in any experiment was 13 ft and the furthest 70 ft. No animals were ever killed at distances further than 18 ft and none was hurt in any observed way at distances further than 50 ft from the explosion, a distance at which the positive component of the blast wave was of the order of 6.3 lb per sq in and the suction component 1.3 lb per sq in. Between 13 and 18 ft almost all animals were killed when placed so that their body walls were affected by hydrostatic pressure (i.e. end-on to the charge). At these distances the positive component of the blast wave (hydrostatic pressure) varied between 126 and 63 lb per sq in".

Although it was clear that different species vary in susceptibility, a relationship was found between body size and blast effect which allowed the results to be extrapolated to man. The work gave results useful to the shelter programme and also to the designers of bombs. By detonating British 500 lb GP bombs among live goats staked out in a pit Zuckerman deduced that the lethal pressure for man is between 400 and 500 psi and crosschecks with air raids on British cities showed this to be of the right order (26). The pressure necessary to cause minimal pulmonary damage was placed at 70 psi.

The research at the Lovelace Foundation in the 1960s and 1970s comprised a major programme of work on the effects of explosions on animals and man. The basic approach adopted was the detailed investigation of individual injury modes by experimental work on animals and extrapolation of the results to man. The work has been described in a large number of reports and papers of which those quoted are only a sample; an extensive listing is given in Reference 7.

The effects of overpressure on the body were investigated using 2,097 animals from 13 different species in experiments in which the overpressures were up to 1,680 psi (116 bar) and the duration time ranged from 0.3 to 400 ms. For present purposes it is the 50% mortality level which is of prime interest. Figure 2 shows the effects of overpressure and duration time at this mortality level for three of the species studied: sheep, goats and rabbits. The data in Figure 2 are from a figure given by Fletcher (8), and quoted by White *et al* (7), which gives data for all the animal species studied.

These results may be extrapolated to man as follows. The extrapolation is generally based on body weight, which for man is conventionally taken as 70 kg. Table 2 gives selected original data from the Lovelace work (6) for experiments on the three species where the mortality was approximately 50%. From these data for mortality close to 50% a linear relation was derived between overpressure and mortality and used to adjust the mortalities to exactly 50%. The impulses were also calculated. Table 3 shows the data for the experiments given in Table 2 standardised to 50% mortality and expressed in terms of impulses. The data in Table 3 are plotted in Figure 3, which shows curves for the three species. Also shown in Figure 3 is a fourth curve for man which has been constructed by extrapolation by body weight of the impulse at fixed duration times; the degree of extrapolation required is slight.

A relation for the 50% lethality of an explosion by overpressure on the body has been derived and is shown in Figure 4. For larger explosions with a duration time of 10 ms or more the curve in Figure 4 was obtained from that in Figure 3 by determining the overpressure from the impulse and the duration time. The scaled distance and scaled impulse were then obtained and the corresponding mass of explosive and distance calculated.

For smaller explosions the curve in Figure 4 is based on a duration time of 5 ms for an explosive charge of 70 lb (32 kg) as given by Zuckerman. Then taking the impulse from Figure 3 the overpressure can be determined, the scaled distance obtained and the mass of explosive and distance calculated. The overpressure is 133 psi (9.2 bar) and the distance 13 ft (3.9 m).

The 50% mortality curve given in Figure 4 is asymptotic to the line for an overpressure of 4.1 bar (60 psi) for large explosions. It is of interest that an overpressure of 62 psi (range 50-75) is given as the tentative 50% lethal value for man for fast rising, long duration pressure pulses by Glasstone and Dolan (27) in the context of the effects of nuclear weapons.

#### Death by Translation of Body

Another important mode of injury by the blast wave is translation of the body. Glasstone and Dolan (27) describe experimental work on this mode using animals and dummies.

In one series of experiments cadavers of several animal species (including sheep and goats) were dropped from the back of a vehicle travelling at speeds between 10 and 60 mph (4.5 to 27 m/s). All animals assumed a rolling posture along their long axis regardless of initial orientation. It was concluded that a person tumbling over a smooth surface might survive even if the initial velocity were high provided he could avoid head injury and flailing of the limbs.





















































