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Review of blast injury data and models

Prepared by
Biomedical Sciences
Chemical and Biological Defence Sector
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for the Health and Safety Executive

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Review of blast injury data and models

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The Chemical and Biological Defence Sector, Porton Down have carried out:

(a) a literature review relating to injuries from condensed phase and vapour cloud explosions; and

(b) an assessment of a mathematical model, developed by WS Atkins Science and Technology, to predict the risks to populations in buildings near to vapour cloud explosions.

It has been found that the Atkins model addresses the *principal* causes of fatal injury for populations in the vicinity of vapour cloud explosions. However, some less common causes of death, such as translational injury and burns, are *not* addressed.

The Atkins model is based on widely used empirical relations and injury criteria obtained from a number of respected sources. However, an exceptionally detailed examination of the source literature, and of archive material to which WS Atkins would not have had access, has shown that many of the injury criteria are not suitable for this application. In particular, the predictions given by the model are likely to be *grossly* pessimistic for most scenarios of interest.

The Atkins model should only be used for scenarios where a high degree of conservatism is required. It is recommended that further research should be carried out to identify more appropriate algorithms and injury criteria.

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Executive summary

The report has been produced for the Health and Safety Executive (HSE) by Medical Countermeasures Department, Chemical and Biological Defence Sector, DERA, Porton Down (CBD) under Order No. 3668/R74.006. CBD were tasked to carry out an assessment of parts of a methodology developed by WS Atkins Science and Technology for predicting the probability of fatality for the occupants of buildings affected by vapour cloud explosions. The parts to be assessed were those concerned with predicting the probability of injury.

Specifically, CBD were to determine whether all relevant injury types, mechanisms and conditional probabilities had been addressed by the Atkins' model, and whether the most appropriate available injury criteria had been used to determine them.

The two main approaches to predicting the probability of fatality for the occupants of buildings exposed to explosions are semi-empirical methods which rely on scaling the casualty data from historical explosions, and methods which model physical effects and injury mechanisms, and then use injury criteria to generate fatality probabilities (*'ab-initio'* approach). Both methods have known drawbacks - inadequately detailed statistical data for the semi-empirical methods, and inadequate or misleading injury criteria developed from first principles.

WS Atkins used an *ab initio* methodology, which aimed to model the physical events of vapour cloud explosions (VCEs) and the effects on buildings. The failure of the building or specific components was then used predict the consequent probability of fatality to occupants, using injury criteria available in public literature.

CBD's search of its own archives, literature in the public domain and contact with some authors, revealed hitherto unrecognised sources of detailed historical casualty data. These searches, and CBD's knowledge of human vulnerability, also revealed flaws in widely accepted and used injury criteria.

Atkins' methodology did address the two injury mechanisms which have been shown by historical data to be the most important causes of fatality in occupants of buildings exposed to explosions: building collapse and flying debris.

The injury criteria used by the Atkins model for predicting death from building collapse are undoubtedly over-pessimistic.

Their model uses the most widely accepted injury criteria available in the world literature for prediction of fatality for impact from flying debris, but unfortunately, these criteria are so flawed that they render the subsequent calculations unsound. CBD's opinion is founded on comparison with detailed data from real events and by examining the original assumptions upon which the criteria were based. The methodology also covers a third possible cause - fatality due to glazing fragments - but grossly overestimates its importance. Flying glass is a major source of mortality from the Atkins predictions; it

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causes virtually no *mortality* amongst the casualties of actual explosions, although it is a major cause of *injury*.

The Atkins methodology did not address four other potential causes of significant fatality in buildings. These are: translational injury within buildings; flying debris originating from sources outside buildings; burns, and primary blast lung injury. Of these, translational injury is a significant potential cause of fatality at the upper end of the range of overpressures considered by Atkins in their methodology. The probability of fatality from the other three mechanisms should be very low for most VCEs, but is not zero.

The flaws in the individual injury criteria would probably result in inaccurate predictions of the total incidence of fatalities in building occupants. Overall, these probabilities should be markedly over-pessimistic, despite the omission of some (lesser) potential causes of fatality. Atkins' comparison of their predictions with historical data underestimates the disparity between those data and their own predictions, since they are not aware of the sources of the most detailed data from WW II and terrorist bombing incidents. Consequently, the final Pressure-Impulse diagrams presented for use in predicting fatality are based on unsound assumptions and criteria.

Atkins' conclusion that they have developed a workable methodology for predicting the probability of fatality for building occupants is not sustainable. Other methods must be used to predict the risk of fatality in buildings exposed to VCEs. The Atkins model is likely to over-estimate the incidence of fatalities.

The best predictive methods currently available are semi-empirical ones which rely on the correlation of injury with damage to structures. Injury criteria in current use are too deeply flawed to form the basis for models relying solely on predictions from first principles. The most profitable approach for the future is likely to involve combining semi-empirical methods with criteria developed from first principles - improved casualty criteria which have been thoroughly validated against (or derived from) historical data.

In addition, CBD's review highlighted the disparity between the typically large numbers of casualties from accidental and terrorist explosions who survive with injuries, and the relatively small numbers of casualties who die. Consequently, the human and financial cost of such explosions may be reflected poorly by predictive models which deal only with fatality.

It is recommended that:

- The WS Atkins model should only be used in its present form if it is required as a relatively crude solution to provide probabilities of fatality known to be conservative.
- The model should be improved and the enhancements validated against all available historical data. New injury criteria will be required; it would probably be necessary to derive these as hybrids from historical and experimental data. Contributions from a number of

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specialist fields will be required - explosion and structural response modelling, combat epidemiology, military surgery etc.

- There should be a thorough review and re-assessment of available and emerging computer models of vapour cloud explosions. CBD's review of these tools was simply an overview. The review should examine the prediction of blast wave characteristics such as pulse shape in the close-in, mid-distance and far-field zones.

- Methods available to predict the effects of different blast wave pulse shapes on structures and debris should also be reviewed - current practice is to approximate complex pulse shapes to simple triangles. These effects should be reviewed with particular reference to the acceleration of objects of all sizes (including humans) by both pressure and drag forces.

- Further survey of recently identified historical data should be undertaken. It should aim to distinguish the contributions of all the different potential injury mechanisms to fatality in buildings exposed to explosion effects. The survey should start with a systematic review of the archives of Lord Zuckerman in Norwich.

- The probability of injury and its severity, as well as the probability of fatality, should be considered in future studies of casualty generation in buildings affected by blast.

Preface

Criticism is easy in any facet of science, technology or medicine CBD acknowledges that the authors of the papers reviewed have undoubtedly striven to provide casualty criteria for public benefit, using the best data to hand at the time. In reviewing the basis of these papers, and the Atkins model in particular, CBD have tapped sources unknown to previous authors. CBD's capabilities in the biophysics of trauma and military surgery have allowed a different perspective on the nature of wounds, and their clinical significance. Solutions are more difficult to specify. Our comments are offered in a constructive spirit; it is our hope that they may be used to improve models designed directly or indirectly to improve public safety.

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1. Introduction

1.1 Contractual information

This report describes a programme of work that has been carried out for the Chemical Hazards Installations Directorate of the Health and Safety Executive (HSE), by the Trauma and Surgery group, CBD Porton Down, part of the Defence Evaluation and Research Agency (DERA), an agency of the UK Ministry of Defence. The work was carried out under contract number 3668/R74.006.

1.2 Remit

CBD Porton Down were asked to carry out (a) a literature review and (b) an assessment of a mathematical model that had been developed by WS Atkins Science and Technology, Epsom, Surrey.

Literature review: The review was to cover the mechanisms and probabilities of fatality and serious injury associated with condensed phase and vapour cloud explosions. The review was specifically to cover only information in the unclassified literature (i.e. information that was already in the public domain, or could be made available).

Model assessment: The WS Atkins model had been produced (under a separate contract to HSE) to predict the risks to personnel from vapour cloud explosions. CBD Porton Down were asked to assess the parts of the model that were concerned with the probability of injury. Specifically, the assessment was to consider (a) whether the Atkins model considered all relevant injury types and conditional probabilities of injury and (b) whether appropriate injury criteria or other algorithms had been used to estimate the conditional probabilities of injury. Where appropriate, recommendations were to be made to address any deficiencies in WS Atkins' model.

1.3 Overview of the report

The report is split into four main parts as follows:

Sources: the sources of information used by CBD Porton Down in support of the review and assessment are summarised in section 2. A reference list is given in section 10.

Background information: this is presented in sections 3-5. Section 3 concerns the physical phenomena associated with explosive events, the types of injury that can be caused by explosions and the mechanisms of injury. Section 4 presents available historical information injury or fatality levels associated with building collapse and displacement injury. Information of this type is particularly relevant to predictive models that extrapolate/interpolate from historical or experimental data (empirical models). Section 5 presents available information on injury mechanisms and other phenomena that are relevant to predictive models that attempt to simulate events based on the underlying laws of physics (first principles or "*ab initio*" models).

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Findings of the review of WS Atkins' model: these are presented in sections 6 and 7. Section 6 gives a brief overview of the Atkins model and section 7 details the findings of the review. In particular, the suitability of the injury criteria used in the model and the injury types addressed by the model are discussed.

Conclusions and recommendations: these are given in sections 8 and 9 respectively.

2. Sources of information

Section 10 is a list of the key texts consulted in the CBD review; it is unlikely that Atkins could have identified or acquired some of the papers acquired by CBD. An overview of the sources consulted for CBD's review of the injury criteria used by Atkins are summarised below:

- The reference list of WS Atkins report - review of the references and acquisition of second, third and occasionally fourth level citations.
- Other publications by authors identified from the Atkins' report, and subsequent citations.
- References already held by CBD, including: historical papers regarding casualties from air raids in WW II (UK and Germany); early research into causes of injury and mortality by British and German scientists; files of references on burns, urban terrorist bombing incidents, urban SCUD attacks from Gulf war; unclassified papers on Fuel Air Explosives (FAEs); major accidental explosions.
- Unclassified text books and technical guides on explosions and their effects, including texts produced by those concerned with loss prevention in the process industries in the UK, US and mainland Europe; textbooks and papers on the effects of nuclear explosions.
- Conference reports, proceedings and minutes from explosives safety seminars.
- Personal contact with some authors.
- MEDLINE searches on earthquake casualty patterns from building collapse, with particular reference to the balance of mortality and injury, and the impact of time-to-rescue on outcome.
- Searches on other specific topics raised by the Atkins report, such as the association between skull fractures and death, and between penetrating wounds and death.
- Output from organisations such as the Explosives Storage and Transport Committee (ESTC), Home Office Emergency Planning Research Group (EPRG) - obtaining advice, copies of papers/reports, information about other models/methodologies.
- Civil Defence Archive material.
- Papers from the archives of Lord Zuckerman.
- Information held in the Public Record Office.
- Technical reports from US nuclear tests in the 1950s - 1970s.

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The Atkins search of databases EMBASE, MEDLINE, OCC SAF & HEALTH, BRIX/FLAIR, MHIDAS were not repeated.

CBD also acquired information on the following models; the review was relatively superficial and undertaken to provide an overview of alternative models:

- HAZMOD - a Home Office casualty prediction tool.
- RISKWIT models by VTT/Siemens Nixdorf.
- HEXDAM & VEXDAM Engineering Analysis Inc., Huntsville, Alabama.
- Kirk's BLEVE & VCE models and simulators, Queen's University, Kingston, Alberta.
- Computer models from TNO, Netherlands - Explosion Prevention & Protection Research Group.
- FLACS and μFLACS by CMR (Christian Michelsen Research AS, Bergen, Norway).
- Other computer models of gas explosions offshore.
- DISPRE (Building debris hazard prediction model) - developed for American Department of Energy (DOE) and Department of Defense Explosives safety Board (DDESB) by Southwest Research Institute, San Antonio, Texas.
- DYNAMAN for bodily translation and impact in buildings.
- EXMOD and sub-programs such as EXFRAG (produced by Lees, University of Loughborough).

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3. Biological effects of blast waves

3.1 Introduction

This section describes some of the important physical phenomena associated with a) condensed phase and b) vapour cloud explosions. The types of injury that are likely to result from these physical phenomena are described and the mechanisms of injury are discussed. The incidence of the various types of injury in specific explosive incidents are outlined.

3.2 Blast effects of condensed phase high explosives

CBD has extensive experience of investigating the physical and biological effects of blast from detonation of condensed phase high explosives, both in free-field and within enclosures. Before considering the physical and biological effects of VCEs, it is appropriate to describe the features of blast effects from condensed phase high explosives, and how these effects can cause human injury and death.

Explosions can result in a wide spectrum of injuries to personnel, and of damage to objects. The effects of detonation of condensed phase explosives have been studied and described exhaustively over many decades. However, it is still surprisingly difficult to specify or predict patterns of injury to people or damage to property, because of the diversity of factors which characterise the explosive event. With the relatively simple predictive problem of condensed phase explosives, these compounding factors include:

- explosive type and quantity;
- presence of reflecting surfaces;
- location of the explosive device with respect to potential targets and debris;
- construction of the device - shape, primary fragments.

An explosion is essentially a rapidly expanding sphere of high-pressure, high-temperature gaseous products resulting from the rapid chemical decomposition of an explosive. The very high initial pressure within this sphere - the overpressure - is effectively an instantaneous rise in pressure for high explosives. The motion of the products results in the 'dynamic overpressure'. The 'shock wave' and the 'dynamic overpressure' are frequently described collectively as a 'blast wave'.

3.2.1 Shock wave

This front of overpressure expanding from the centre of the explosion is initially faster than the speed of sound in ambient air, and has a very high peak pressure. The peak overpressure declines very rapidly with distance (Figure 1). The velocity of the shock front also declines.

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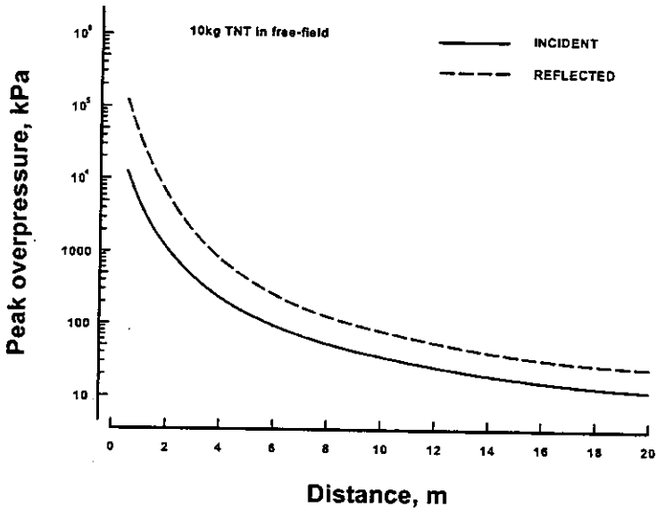

Figure 1: Overpressure/distance relationship for 10 kg TNT in air

A shock wave from condensed explosive is shown in Figure 2.

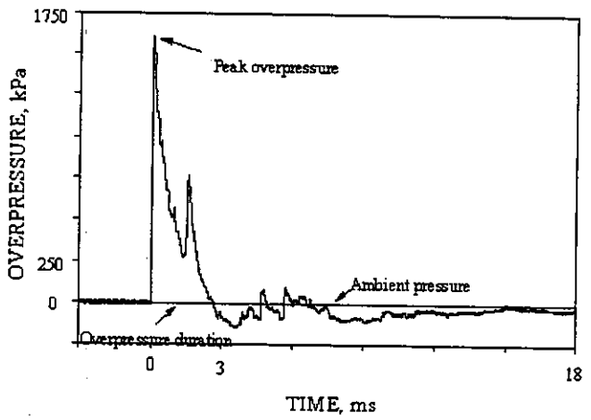

Figure 2: A shock wave in air from a suspended charge of condensed phase high explosive; the peak on the trailing edge is a reflection from the ground

The two principal determinants of the damaging power of a shock wave are the peak overpressure, and its duration. Reflection of the incident wave at a surface can reinforce the oncoming wavefront and result in a loading on the surface up to eight times the incident overpressure.

The interactions of shock waves with objects may be extremely complex and this accounts for apparently idiosyncratic effects of explosions. For example, reflection and diffraction may result in the

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death of an individual from primary blast injury a very short distance from another person, who remains completely unscathed. A soldier exposed in the open to an explosion may exhibit no primary blast injuries, but a comrade taking refuge in a nearby trench may succumb because of reflections within the field defence enhancing the pressure loads to the body.

3.2.2 Dynamic overpressure

This pressure results from the movement of air behind the shock wave. The motion of air will also exert drag forces on an object. The dynamic overpressure can be many orders of magnitude greater than those of the strongest climatic winds, and may therefore cause significant motion of objects. Close to an explosion, the dynamic pressure may be as great as or greater than the 'static' overpressure from the shock wave, although further from the explosion it falls off more rapidly.

The very high wind-speeds associated with blast overpressures are emphasised by the fact that a hurricane force wind of 125 mph only exerts a dynamic overpressure of 0.25 psi. (see also other examples in Table 1). This figure sounds unimpressive, until considered in association with the number of square inches in the frontal silhouette of an upright human body. The load on the body may be very high, resulting in displacement. A long duration shock wave with peak side on overpressure of 10 psi is associated with a peak dynamic overpressure of 2.2 psi, from a wind velocity of 294 mph. This level of peak static overpressure presents no threat to life from primary blast injury to lungs or other vital organs, but a finite risk of death from bodily displacement or the impact of missiles.

Peak static overpressure (psi)	Peak dynamic pressure (psi)	Maximum wind velocity (mph)
200	330	2078
150	222	1777
100	123	1415
72	74	1168
50	41	934
30	17	669
20	8.1	502
10	2.2	294
5	0.6	163
2	0.1	70

Table 1; Overpressure and dynamic pressure related to maximum wind velocity (long duration overpressures)

3.3 Blast effects of vapour cloud explosions

An accidental vapour cloud explosion is a very different event from a detonation of condensed high explosive. The volume of flammable gas, mixed with air, has stored chemical energy. The central problem in assessing the hazard posed by such clouds is how this energy is dissipated.

If all the energy contained in a large pre-mixed cloud could be released from a ***point*** by an efficient ***detonation*** to result in a ***shock wave***, calculating the effects would be relatively straightforward. The equivalent mass of TNT with the same stored energy as that of the cloud could be determined, and the

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expected damage predicted from well-known TNT data. This would be valid for both damage to people and to buildings.

In practice, the events in a VCE will be very different from the hypothetical process described in the previous paragraph. A vapour cloud event which would come closest to the hypothetical process would be the detonation of a military fuel air explosive (FAE), which when functioning 'ideally' forms a homogeneous cloud of a stoichiometric mixture which is then *detonated* by initiators. In such circumstances, a single tonne of hydrocarbon in an ideal mixture with air could theoretically release the same energy in its blast wave as that in ten tonnes of TNT. In practice, a blast energy release equivalent of 2 or 3 times the same mass of TNT is about the maximum achievable by such weapons.

Moreover, although the explosion produces a shock wave of classical shape in the case of true detonations of FAEs - albeit of longer duration than would be expected from a TNT equivalent - it does not behave as if emanating from a very high pressure point source. In practice, the detonation produces an overpressure of ~20 bar throughout the cloud - which is usually shaped like a large thick pancake. The shock wave emerges from the edge of the cloud with a peak overpressure of ~20 bar, and its overpressure thereafter drops approximately in accordance with the inverse cube law, applied to distance from the edge of the cloud, not the centre.

Although the centre of the explosion does not reach overpressures as great as those generated by the equivalent mass of TNT, the in-cloud pressure of ~20 bar extends to a much greater radius than the same overpressure from the TNT explosion. Only in the outer 'far field' will overpressures cease to be significantly different from those produced by the equivalent mass of TNT. These characteristics make military FAEs very effective weapons. A shock wave overpressure of ~20 bar is well above the threshold for producing lethal primary blast lung injury in humans, and will destroy most structures. Thus, the lethal radius for primary blast injury is much greater for FAEs than for the equivalent TNT, as is the radius for destruction of even quite strong structures. Only structures deliberately hardened to resist overpressures above 20 bar would be more efficiently attacked with the equivalent mass of TNT, delivered with precise accuracy.

Thus, a VCE blast threat may potentially exceed that from a point release of the same amount of stored energy. Fortunately, accidental VCEs in industry usually behave very differently. Rarely is all the released fuel included in a perfectly homogeneous stoichiometric mixture (parts of the cloud will be too rich, parts too lean, and some may have dissipated). Vapour clouds are almost invariably *ignited* at a peripheral point by a low energy flame ignition source. This may result, in an unconfined cloud, in a flash fire or a slow deflagration to produce only negligible overpressures. If there is significant confinement and/or congestion, flame speed and turbulence will increase, resulting in faster deflagration with generation of higher overpressures *but only in the affected parts of the cloud.* However, it is unusual for these overpressures from *deflagration* to exceed 1 bar, and the maximum achievable is probably about 8 bar. Moreover, the blast wave will normally be a pressure wave (with a finite rise time), rather than the more damaging shock wave (with a near-instantaneous rise time - see Figure 3). However, it may have a long duration and a considerable impulse. Overall, a VCE which

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produces a significant explosion usually releases in the order of only a few percent of its available energy as blast, since much of the cloud is consumed by flash fire or slow deflagration, generating little overpressure.

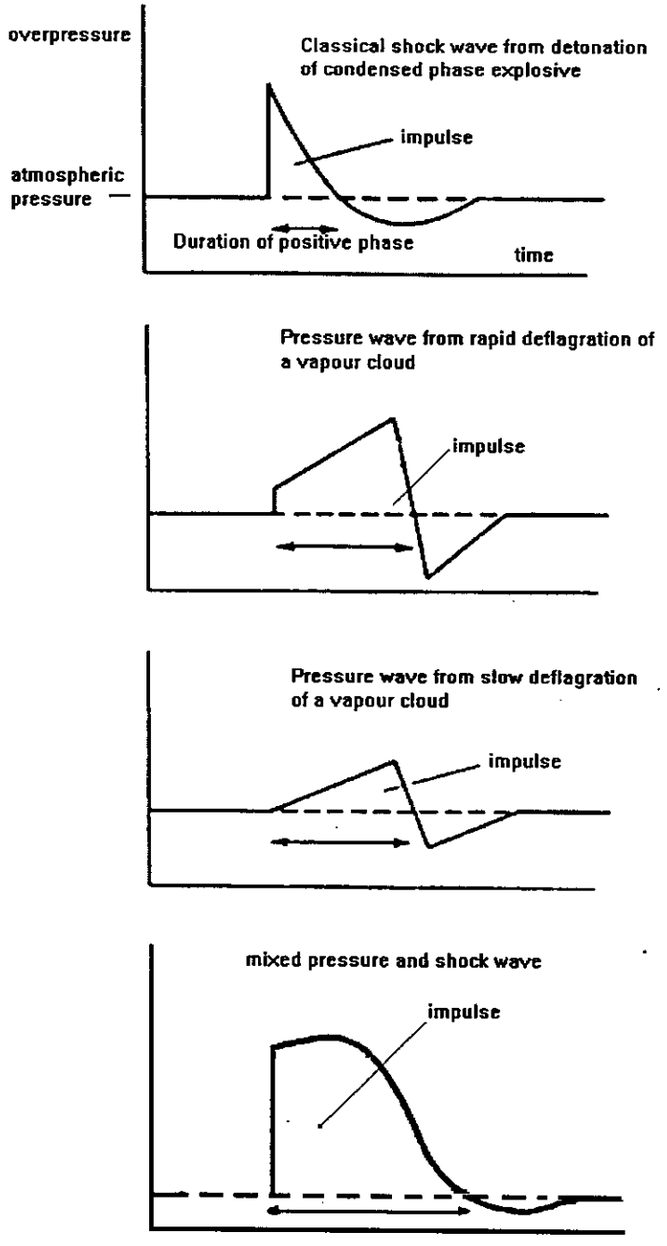

Figure 3: Shapes of shock and pressure waves (redrawn from several sources)

Rarely, deflagration may proceed to detonation by flame acceleration or local confinement. "Bang Box" effects from semi-closed spaces within the area of a deflagrating cloud are a potent cause of this escalation. If detonation occurs, it may then propagate through an extensive proportion or even all of the cloud. This may include those unconfined areas which would have been consumed only by slow deflagration or flash fire if the phenomena in the confined areas had been restricted to fast

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deflagration[1]. In this event, the percentage of available energy released as blast may be orders of magnitude greater than that normally achieved by deflagrating VCEs; their overall efficiency of release of energy as blast is normally of the order of only a few percent. If widespread detonation occurs, the total energy released as blast may, at worst, be several times that which would be produced by the same mass of TNT. Moreover, the blast wave will then be a shock wave, not the slower-rising pressure wave produced by even the fiercest deflagrations. Figure 4 provides a summary of the consequences of the accidental release of a volatile hydrocarbon.

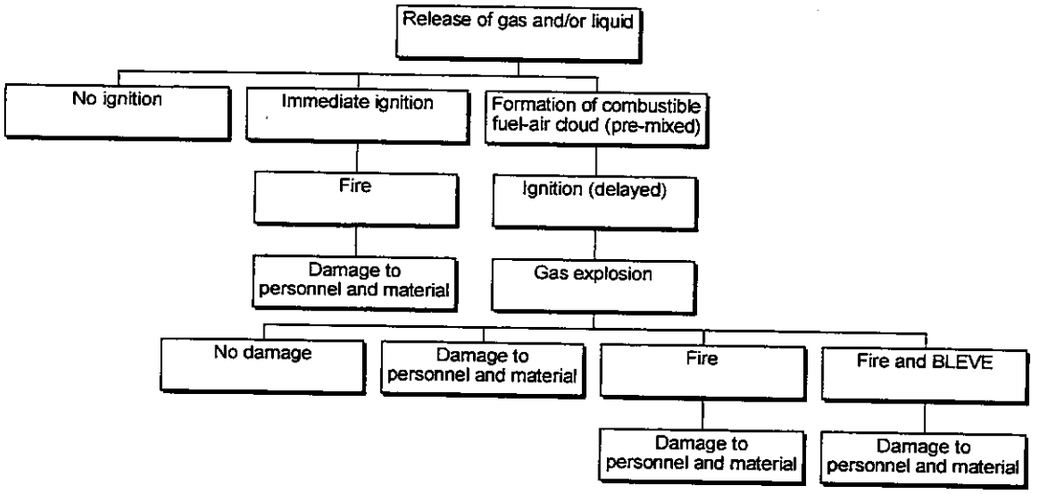

Figure 4: Consequences of accidental release of volatile hydrocarbon (redrawn from several sources)

At present, there is very limited historical information available about the effects of slow rising pressure waves from VCEs on people, buildings, or on people in buildings. Quantitative information is particularly lacking. Applicable quantitative experimental data is also limited.

One approach to overcome this lack of data is to study the relationships between building damage from better documented cases involving detonation of condensed phase explosives, or from natural events such as earthquakes. Occupant mortality could be predicted by comparison and extrapolation. The validity of any such comparisons and extrapolations would require stringent validation if they were to be used quantitatively for predicting the probability of fatality in a given set of VCE circumstances, with real safety distances and planning decisions being based upon them.

Another approach is to use the pre-existing theoretical models and use mathematical corrections for the different pressure time history of pressure waves, since all existing models are based on shock waves. These models purport to predict casualties from condensed phase explosions both qualitatively and quantitatively, by examining and quantifying particular explosion effects (e.g. primary blast injury, flying glass, translational effects, building collapse, flying debris) and then predicting injuries and/or

[1] The flame speed -(and generated overpressure) of a deflagration in a congested and semi-confined area drops rapidly once the process emerges into a clear and uncongested/unconfined area. Consequently, little of the energy in the unconfined area of the cloud is released as blast.

fatalities quantitatively by combining assumptions about mechanisms of injury with further assumptions about injury or fatality criteria. By combining the results of such formulae for all injury mechanisms, it should be possible to predict fatality (or injury) rates at a given location if such factors as blast wave amplitude, shape and duration, and physical characteristics of environment (e.g. building construction, proximity to glass windows) are known.

This is a superficially attractive option, since the reasoning and assumptions expressed in the descriptions of these predictive models seem correct intuitively. For example, it seems self-evident that a person hit by a number of fast-moving glass shards will be at a finite risk of mortality, or that a person within a building which is completely demolished by blast would be lucky to survive. However, the key question here is: what actually happens in reality? Such models invariably contain one or more obvious assumptions when linking physical events, injury or fatality criteria and injury or fatality rates. Validation is required if they are to be employed for quantitative predictions in matters of safety.

The ideal validation would be to compare the modelled scenario with a scenario exactly the same, reproduced experimentally, or with an identical or sufficiently close historical incident. The former is impracticable for ethical reasons; many attempts have been made to go part of the way with animal studies and then extrapolate to the human case, but although some have been useful, all have involved further assumptions, and some have been notably misleading. This leaves the alternative of historical experience - records of war-time or accidental explosions. They should be well documented enough to deduce overpressures and durations at the casualty locations with confidence, and the casualty details should be well recorded - not only clinical details of injuries and outcomes, but also of building construction and eventual physical state, position (and posture) of each victim in which room, and a multitude of other details. Again, such data are overwhelmingly likely to pertain to condensed explosives, but at least they provide a basis, either for calculation or speculation.

3.4 Injury classifications

Injuries from explosions can be classified into five groups:

- **Primary:** Primary air-blast injuries are produced by the direct effect of the shock wave on the body. The shock wave produces a high acceleration of the body wall, transmitting the shock wave into closed body cavities. The dissipation of this energy within the body at the interfaces of tissues with different acoustic impedances, or at the interfaces between tissue and air results in damage to tissues. Primary blast injury can cause injury or death by damaging the lungs, the gut and the solid intra-abdominal organs. Injury to the ear is also a primary blast injury.

- **Secondary**: These injuries are produced by the impact on the body of missiles - fragments of the explosive device or debris from the environment. The injuries may be either

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penetrating or blunt (non-penetrating). Injury from falling debris in buildings which are damaged or destroyed by blast is also classed as secondary blast injury.

- **Tertiary:** These result from gross displacement of the body by the blast overpressures. In the immediate vicinity of the explosion, total disruption of the body may occur. Tertiary injuries result from the impact of the moving body on hard or sharp parts of the environment; they also include traumatic amputations.

- **Burns:** Burns from detonation of condensed explosives are usually "flash" burns from radiation or convection from the explosive products. Occasionally, clothes or parts of the environment may catch fire resulting in flame burns. Inhalational injury may occur from smoke and hot gases. Burns from radiant heat or contact with flame may be a more serious risk with some VCEs. Burns are potentially a major cause of severe injury and death in BLEVEs[2];

- **Psychological:** The psychological effects of being exposed to accidental explosions are not directly lethal, but it is well known from military practice that they can result in major long term problems such as PTSD. Idiosyncratically, psychological trauma might lead to death by suicide, or by dangerous changes to behaviour patterns.

In addition, a common consequence of explosions is combined injury - individual victims affected by more than one injury mechanism. Several injuries which in isolation have a very low risk of lethality may have a cumulative effect and thus may result in death.

3.5 Injury mechanisms

This section describes the injury mechanisms associated with the injury classifications outlined in section 3.4

3.5.1 Primary blast injury

Primary blast injury is caused principally by the coupling of a shock wave into the body. The stress wave generated will propagate in body tissues and reflect within body cavities. The blast loading will also produce gross compression of the body wall to result in local shear, and the generation of shear waves. Primary blast injury is rarely seen in isolation in surviving military casualties. With most conventional exploding munitions, proximity sufficient to produce a even a small risk of primary blast injury also renders the victim at high risk of fatal injury from fragments. In the military context, primary

[2] BLEVE: (Boiling Liquid, Expanding Vapour Explosion): The explosively rapid vapourisation and corresponding release of physical energy of a liquid, upon its sudden release from containment under greater-than-atmospheric-pressure, at a temperature above its atmospheric boiling point. The physical energy released during flash vapourisation may cause a signficant pressure wave or shock wave. Large pieces of the containment vessel may be propelled considerable distances as very hazardous fragments; large hollow fragments, eg half of a vessel itself, may undergo 'rocketing' and travel unexpectedly long distances, due to the extra energy available from the liquid entrapped in them. If the released liquid is flammable and ignites immediately, a fireball will usually result. If it does not ignite immediately it may mix with air and the resultant cloud of vapour ±mist will present a potential vapour cloud explosion hazard.

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blast injury may be seen if FAEs are employed. Primary injury is also seen in some terrorist incidents where large bare charges are employed. The risk of primary blast injury from large nuclear weapons was the driving force for much research on blast injury in the 1950s - 1970s.

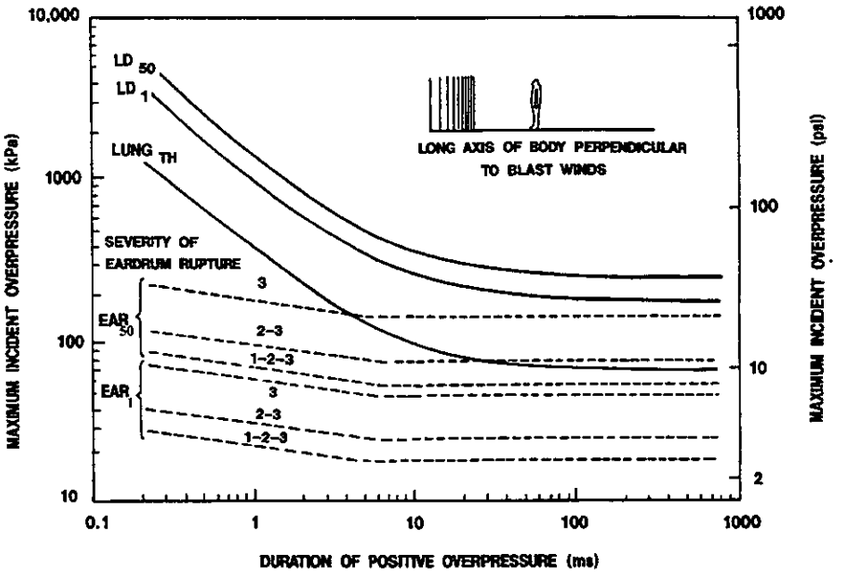

Figure 5: Predicted susceptibility of the lungs and ears to blast overpressure

Large overpressures are required to produce lung injury. The risk of injury is dependent upon many features of the actual exposure but the key factors are the peak overpressure and the duration. The shorter the duration, the greater overpressure is required to produce a given level of lung injury. The relationship between these two parameters is complex; the relationship is outlined in Figure 5. This figure shows the probability of mortality from blast lung for a body stood facing an explosive device - similar curves for prone orientation and proximity to reflecting surfaces are also available. They are often referred to as the Bowen curves (Bowen, 1968). $LUNG_{TH}$, LD_1 and LD_{50} are thresholds of lung injury, 1% and 50% probability of death from blast lung within 24 hours if untreated. The figure is taken from Richmond and Axelsson, 1990; criteria for other orientations of the body are in the reference.

It must be emphasised that all these figures and predictions are for shock waves of the classical high-explosive shape - effectively instantaneous rise time and an exponential decline to ambient pressure. There is very little data on the primary effects of slow-rising pressure waves such as those produced close to deflagrations.

The most notable feature of the Bowen curves is the very high overpressure required to produce lung injury with small quantities of explosive (short duration). For a duration of 2 ms, an incident overpressure of 800-1000 kPa is required to result in 1% mortality. Lung injury is evident from about 400 kPa but this threshold results in quite trivial lesions.

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It is important to recognise that the tolerance curves apply to single shock waves in free-field. The detonation of a condensed phase explosive in a confined space produces a complex pressure environment comprising multiple fast-rising peaks from internal reflections of the incident shock wave, and a longer duration 'quasi-static' overpressure augmented by the combustion products. Beyond 20 ms duration (generally termed 'long duration' blasts), the risk of lung injury is dependent upon peak overpressure alone.

Attempts have been made to tabulate the data contained within the Bowen curves. This inevitably simplifies the relationships but does provide general guidance on the susceptibility of man to short and long duration shock waves; Table 2 is an example.

Effect	Effective Peak Pressure (psi) - long duration pulses	Effective Peak Pressure (psi) - short (3 ms) pulses
Lung Damage		
Threshold	12 (8 - 15)	37-49
Severe	25 (20 - 30)	98
Lethality		
Threshold	40 (30 - 50)	112-156
50 percent	62 (50 - 75)	156-217
100 percent	92	217-302
Eardrum Rupture		
Threshold	5	5
50 percent	15 - 20 (more than 20 years old) 30 - 35 (less than 20 years old)	15-20

Table 2: Criteria for primary blast effects in man - long and short duration pressure pulses.

Table 3 presents an over-simplified relationship between blast overpressure for short duration shock waves and victim groups from injuries to the lungs and ears. It has been used for the categorisation of primary blast casualties (Mellor & Cooper 1989) and is discussed in more detail in a later section.

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Group	Overpressure (psi)	Blast Loading
1	<20	Minor: at maximum, rupture of eardrums
2	10-50	Moderate: primary lung damage in minor number of casualties
3	50-80	Severe: sufficient overpressure to cause lung injury in a significant proportion of casualties
4	>80	Very severe: sufficient overpressure to cause severe primary lung damage with a significant risk of death.

Table 3: Simplified victim groups according to blast loading from terrorist bombs - short duration pressure pulses.

3.5.2 Secondary blast injury

Secondary blast injury is caused by objects accelerated by the explosion - these may be parts of the casing of a military anti-personnel weapon, or may be parts of the surrounding environment. In most military and terrorist explosions, these missiles (primary and/or secondary fragments) are the major cause of death and injury. Debris falling under the influence of gravity, for instance when a building collapses due to blast, also causes secondary injuries.

All projectiles perform work upon the body - lacerating, contusing and displacing tissues. The capacity of a penetrating projectile to perform work is defined by its available kinetic energy ($\frac{1}{2}mv^2$ - units are Joules when m is in kg and v is in m/s). The available kinetic energy defines only its capacity to perform work on tissue - the proportion of this energy that is ultimately transferred at each centimetre along the track is determined by the degree of retardation of the projectile by the tissues. The retardation forces are principally dependent upon:

- the square of the velocity, and the mass of the projectile;
- the presented area of the missile;
- the density of the tissues.

Retardation transfers energy, and this energy is used to do work, lacerating and stretching the tissues.

The available kinetic energy is 1,500 - 3,000 Joules for military rifle bullets and most bullets from handguns have available energies around 300 - 500 Joules. Military anti-personnel fragments have low available energies and in those casualties surviving to reach surgery, available energies ranged from about 10 - 150 Joules. The available energy from environmental fragments will encompass this whole range.

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An appropriate classification of the work performed within a wound is the "energy-transfer". It is important to differentiate between mechanical distortion (work) that arises from the energy-transfer and the patho-physiological consequences of this distortion. Some elastic tissues may have significant work performed on them but only modest tissue injury results. Further, it is important to realise that projectiles may produce indirect injury to tissues not directly in their path.

A general classification of the extent of soft and bony tissue involvement is based upon the incidence of indirect injury. In *low energy-transfer wounds*, soft tissue injury is confined to the track of the projectile. The wounds arise simply from the cutting action of the projectile as it penetrates the tissues.

In *high energy-transfer wounds*, injury usually occurs radial to the track of the projectile in addition to the mechanical disruption (laceration and crushing) produced directly. The indirect injury peripheral to the track is produced principally by the formation of a temporary cavity (with non-fragmenting projectiles), a consequence of increasing levels of energy transferred.

It is important to recognise that wounds cascade within these two extremes - these are not rigid classifications providing only two niches for wound severity.

The outcome of wounds depends on the nature of the wound and upon the timeliness and quality of medical care. The latter are important issues in war but less prominent in civil incidents.

The clinical effects associated with these events are determined by the role and function of the tissues traversed by the projectile, or injured by the temporary cavity. For high-energy transfer wounds, the physical disruption produced by the temporary cavity is determined by the mechanical properties of the tissue and its surroundings. For example, a temporary cavity within lung produces relatively minor injury because of the low density and high elasticity of the tissues. A high energy-transfer wound to the brain or liver results in severe damage to these friable organs and disruption of their coverings - bone in the case of the brain and the capsule for the liver. High mortality is associated with high energy-transfers to these organs.

3.5.3 Tertiary injury

Tertiary (translational) blast injury is caused by the physical acceleration of the body by the blast wave. The body may strike the ground, blunt or sharp objects with sufficient force to cause injury. Arrival of the shock wave will initiate such acceleration, but the dynamic overpressure is usually the major contributor to this mechanism - it follows that with most conventional explosions the victim must be quite near to the explosion to be susceptible to such forces, and thus will usually be at considerable risk of secondary blast injury. Traumatic amputation by the blast wave - which is accompanied by a high risk of death from consequent haemorrhage - is also classified as tertiary injury, but is only seen at very high overpressures, unlikely to be reached in VCEs.

Mellor and Cooper (1989) used the Army's computerised database of military casualty details (HACS) to analyses the cases of 828 servicemen injured or killed by terrorist explosions in Northern Ireland

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between 1970 and 1984. Because of the nature of the conflict in Northern Ireland, the magnitude of each explosion, the severity of building damage at given ranges around it, and the distance of the victims from it were usually known quite accurately, and likely blast overpressures could be deduced. This permitted division of the casualties into simplified subgroups as shown in Table 3. Considering only overpressures and ignoring pulse shapes, these results provide support for the tacit assumption that in VCEs, fatality from primary blast injury should rarely be a consideration, except perhaps within the boundaries of the vapour cloud. It would be very unusual to encounter pressures of 20 psi or more from VCEs, except in the cloud, unless detonation rather than deflagration occurred.

Note however that an overpressure of as little as 5 psi may cause the collapse of buildings (Table 4) resulting in a significant risk of injury or death to people within. Being under cover may be an attractive option for shielding from fragments, but may be a fatal miscalculation if the cover collapses. Being within a mechanically strong cover (such as a control building) near a large explosion may also be lethal, if the blast can enter and load the body repetitively.

Pressure (psi)	Structural material
0.1 - 0.5	Shatter single strength glass
1 - 2	Crack plaster walls Shatter asbestos sheet Buckle steel sheet Failure of wood wall
2 - 3	Crack cinder block wall Crack concrete block wall
2 - 8	Crack brick wall
5 - 10	Shatter laminated car safety glass

Table 4; Blast pressure effects upon structures on open ground

From the medical or casualty-production point of view, the important direct effects of blast loading are: penetrating wounds or blunt trauma from secondary or tertiary injury, traumatic amputation, and primary blast injuries to the ear, lung and gut. With the exception of ear injuries, all these effects can produce fatalities.

3.5.4 Burns

Burns are another potential cause of injuries and deaths from explosions. Flash burns are common in people sufficiently close enough to the detonation of a condensed high explosive to receive radiant heat from the products cloud, or engulfed by hot gases and receive heat dose to the skin from convection. The duration of the thermal dose is very short (< 0.5 s) for most conventional explosives and so the burns are usually superficial and heal quickly. FAEs and nuclear weapons have a longer heat pulse; these will produce more severe burns.

Vapour cloud explosions may produce longer thermal outputs, especially if deflagration predominates or there is an associated flash fire. In some circumstances, victims might be within the area of the

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cloud but not sustain fatal blast injury - they would be at risk of serious flame burns. BLEVEs, which may co-exist with vapour cloud explosions, comprise a special case of serious risk of injury and fatality from burns - both from direct contact with the fireball and from radiating heat at surprisingly long distances. Ignition of clothing, the contents of houses, or other objects by radiant heat will produce much more serious burns in people close to these secondary sources than would be caused by the initial radiant heat. Although burns are not a 'blast' effect (and the scope of the survey specifically excluded burning vapour clouds), burns could be a potential cause of fatality - and certainly of injury - in vapour cloud explosions, especially if associated with BLEVEs. Further discussion and data on the burn threat (including quantitative risks and formulae for calculating them for BLEVEs) can be supplied if required.

3.5.5 Multiple injuries

Multiple injuries are a common feature of explosions. The different combinations of the whole spectrum of blast effects can reproduce a whole range of injuries ranging from those produced by bullets to the type of injuries observed in civilian traffic and industrial trauma. It is important to remember that a 'blast' casualty can have one, or a combination or any number of, these types of injury. For example, a casualty close to a condensed explosive terrorist bomb - or a VCE/ BLEVE - may have any or all of the following: ruptured eardrums, eye injuries from flying glass, penetrating or blunt fragment injuries from parts of the environment, burns from fuel, smoke inhalation damage to lungs, the early stages of primary 'blast lung', head and/or visceral injuries from being propelled against a wall. Each of these injuries may be simple to treat in isolation and readily survivable, but together they could potentiate to result in a confounding pattern of trauma that makes the treatment of the patient very difficult. 'Polytrauma' ending in death through 'Multiple Organ Failure' would be the feared outcome.

3.6 Casualty patterns in specific explosive incidents

The casualty patterns produced by explosions within or close to populated areas may be reviewed by considering urban terrorist bomb explosions, accidents with explosives, and events such as the Scud attacks on Israel in the 1991 Gulf War. The following sections give an overview of the injury patters that were observed in a number of explosive incidents:

- Bologna bombing;
- Texas City disaster;
- Experience in the Gulf War;
- Oklahoma City bombing.

3.6.1 Bologna bombing

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Brismar & Bergenwald (1982) described the casualties from the Bologna terrorist bombing and stated that secondary effects from flying objects and collapsing building material were the predominant causes of casualties, rather than primary blast effects. The environment around the focal point of the explosion was decisive for the extent of the secondary effects. Part of the building collapsed, crushing people to death or causing severe injuries. In addition, injuries from building stones flying through the air or falling to the ground were predominant (compared to glass - normally more predominant in bombings within cities). They stressed the importance of the construction and internal equipment of damaged buildings in determining the panorama of injury.

They also described the classical pattern of casualties seen in such incidents - a large number of slightly injured persons, a small number of persons with severe injuries, and a varying number of deaths. They emphasised that the majority of deaths seemed to have been caused by crush injuries when the station building collapsed.

3.6.2 Texas City disaster

In the Texas city disaster (Blocker & Blocker 1949), around 2000 tons of ammonium nitrate in a ship exploded; it was followed by an explosion on another ship. The weight of flying debris ranged from a few ounces to several tons, with 1-2 ton fragments found 4,500 feet from the blast. Parts of the ship's cargo were found up to 10,000 feet away. Again, there were many lightly injured, and a characteristic finding was of numerous punctate lacerations, usually from glass particles. They were particularly prevalent on the head and extremities - a consequence of the protection of other areas by clothing. There were many eye injuries.

In 1st zone (up to 1000 feet), those in the open were exposed to the barrage of missiles and suffered more severe injuries than those inside the collapsed buildings (note that this was an unusually fragment-rich environment because the explosion was within the ship). In the second zone (1-2000 feet) *major injuries were found almost entirely in persons in buildings which had disintegrated from the force of the explosion*. In 4th zone (3-4000 feet), injuries were mainly minor, principally lacerations from flying glass. At 10 miles, a girl standing by a plate glass storefront window was deeply cut on her knee by falling glass. At 8 miles, a man's abdominal wall was pierced by glass while lying in bed. *There were no deaths from flying glass.*

Caro & Irving 1973, reviewed the Old Bailey bomb explosion; they described mainly minor casualties who did not require hospital admission. Most of the injuries had been caused by flying glass - but again, *there were no deaths from flying glass.*

3.6.3 Gulf War experience

In a survey by Karsenty *et al* (1991) of casualties from SCUD attacks on Israel in the Gulf War 1991, 46.6% of wounds were from glass splinters, 31.1% blunt contusions and 22.2% of cases were psychological. There were 2 deaths - the result of crushing by fragments of collapsed concrete

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buildings. They commented that the type of building construction affected casualty generation. In reinforced concrete buildings, injuries were mainly minor ones from glass splinters, flying debris and building fragments. However, destruction of a small one storey houses was almost total, resulting in entrapment of personnel. Only one glass splinter produced a dangerous injury - penetration of the skull of a girl. Karsenty *et al* also observed blunt secondary injury within buildings - contusions related to impact by objects.

3.6.4 Oklahoma City bombing

Mallonee *et al* (1996), describing casualties from the Oklahoma City bombing (1.8 tonnes ANFO) emphasised the role of building collapse in fatal injuries, and the role of glass and other flying debris in minor to moderate injuries. The thorough survey included using a building occupant and survivor survey, hospital records, pathologists' records, and plans of the buildings. Multiple injuries were the main cause of death (73%) followed by head trauma (14%). People in collapsed regions of buildings were significantly more likely to die. Of survivors, 66% injuries were from flying glass, 43% due to falling ceiling material, light fixtures or debris, and 33% by being pushed or pulled against an object by the force of blast - *tertiary injury within buildings*. Again, the authors regarded building collapse as a major risk factor for death.

3.6.5 Comment

These representative reports of casualty patterns from detonations of condensed explosives in or near to urban areas are instructive, since they highlight the apparent importance of building collapse as a cause of serious injuries and death, and appear to contradict the predictions of most '*ab initio*' models[3] developed from biophysical principles, in that flying glass emerges as a major cause of injuries, but as a low or negligible cause of death.

An important caveat is that within these papers, it is impossible to differentiate with certainty between death from building collapse alone, and other primary, secondary and tertiary causes of deaths occurring in demolished buildings. This will be considered further below in the context of UK WW II casualty data from aerial bombing of urban areas. The mortality from earthquakes - in which building collapse occurs without primary blast, flying debris, or tertiary effects - is also discussed below.

[3] In the context of this report, models are classed as either (i) 'Semi-empirical' or 'historic' methods which rely on scaling the casualty statistics from historical explosions; (ii) methods which rely on the ability to model the relevant physical effects and injury mechanisms mathematically and then use casualty criteria to produce injury and/or mortality figures - *ab initio* models.

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4. Historical data on injuries and fatalities

4.1 Introduction

Data from historical sources is variable in quality and reliability. The scope of the original data collection may not address current requirements and some key features of the data may reside in personal records. Nevertheless, it does offer an opportunity to review causes of injury from documented explosive events.

4.2 Building damage

The first step in determining effects of blast on buildings and the subsequent casualty ratios, is an evaluation of the blast damage mechanisms which actually occur when a blast wave interacts with a building or structure. These phenomena have been investigated extensively during nuclear tests, and are well described and quantified. Extensive descriptions of the mechanisms, and formulae to quantify them, are to be found in Glasstone and Dolan (1980), Baker (1983) and Lees (1996). Note that the formulae, graphs and models described are derived from high explosive and nuclear tests, and can only be applied with confidence to predicting damage caused by steep rising shock waves.

Predictive models can be checked against well-documented historical events; by far the best documented are the WW II air raids on London. These are recorded in the Zuckerman archive and reported in Hadjipavlou and Carr-Hill (1986). The data that follow are condensed from Hadjipavlou and Carr-Hill (1986), with further direct help from Dr Carr-Hill in recent personal communications (Carr-Hill 1997).

Categories of UK house damage defined in WW II and used as standard since then are given in Table 5 (from Hadjipavlou and Carr-Hill 1986). These refer to typical British brick-built houses - most of the categories of damage given by Glasstone and Dolan (1980) are for wood frame buildings[4].

[4] Glasstone and Dolan use a different descriptive system, defining severe damage as shattering of the frame resulting in almost total collapse. Modest damage occurred where the wall framing had cracked, roof severely damaged and interior partitions blown down. Light damage to corresponded to windows and doors blown in and interior partitions cracked.

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Type of Damage	Description
A	Houses completely demolished - i.e. with over 75% of external brickwork demolished.
B	Houses so badly damaged that they are beyond repair and must be demolished. Property included in the category if 50-75% external brickwork is destroyed, or in the case of less severe destruction, the remaining walls have gaping cracks rendering them unsafe.
Cb	Houses rendered uninhabitable by serious damage, needing repairs so extensive that they must be postponed until after the war. e.g. partial or total collapse of roof structure; partial demolition of 1 or 2 external walls up to 25% of the whole; severe damage to load bearing partitions necessitating demolition and replacement .
Ca	Houses rendered uninhabitable, but reasonably quickly repairable under war-time conditions; damage sustained not to exceed minor structural damage, and partitions and joinery wrenched from fixings.
D	Houses requiring repairs to remedy serious inconveniences, but remaining habitable. e.g. damage to ceilings and tiling; battens and roof covering; minor fragmentation effects on walls; broken window glass. NB cases with <10% of windows broken are not included in this category.

Table 5: WW II UK Damage categories for housing (Hadjipavlou and Carr-Hill 1986)

Such categorisation of housing (or other building) damage permits us to relate building damage to blast overpressure in quite precise quantitative terms, especially if factors such as shielding can be identified, and the precise details of construction are known. When using the standard damage categories, the average circle radius (ACR) is defined for each damage category to be considered: - this is the distance at which the number of dwellings undamaged within a circle of that radius is equal to the number damaged outside the circle. The ACR's for A, B and C_b damage from V1 and V2 explosions in WW II are given in Tables 6 and 7 respectively.

Damage Category	Peak Overpressure(psi) (calculated)	Extreme Maximum Distance	Average Maximum Distance	ACR	Range of ACR
A	20	136	98	72	40 - 95
B	10	170	128	102	70 - 128
Cb	3.8	314	218	172	120 - 220

Table 6: Damage Data for 19 V1 Incidents (charge approximately 0.5 ton TNT); distances in feet

Since the charge weight of the warheads was known, and distance from the explosion to any damaged building under consideration could be measured accurately, it was possible to estimate the likely blast

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overpressure quite accurately. There were many such events from which to collect data. These data are for 1, 2 and 3 storey houses, detached and semi-detached or terraced houses with 9 inch or 11 inch cavity walls.

Damage Category	Peak Overpressure (psi) (calculated)	Extreme Maximum Distance	Average Maximum Distance	ACR	Range of ACR
A	16	186	103	80	30 - 120
B	9.5	202	136	105	60 - 150
C	3.2	475	257	201	140 - 330

Table 7: Damage Data for 100 V2 Incidents (charge approximately 0.5 ton TNT); distances in feet

The pressures at the ACR for A and B damage are about 16 - 20 psi and about 10 psi respectively. The wide variability in the ACRs in Tables 6 and 7 can be explained by the variation in shielding and orientation in this war data from urban areas, and by the variation in type of house and percentage of apertures in the walls.

Note also that these damage figures are for a classical shock wave of relatively short duration, from approximately 0.5 tonne of TNT.

The UK WW II bombing data can be used in more complex ways than tabulating distances and ACRs against overpressures for damage. The data can be used, for example, to calculate the probability of a given level of damage to a building at a particular distance. Damage of different categories can also be correlated with "quantity distance" and other derived factors, most of which are functions of charge weight and distance from charge, and therefore related to overpressures.

Thus, ACRs for different categories of damage can also be predicted from a number of formulae relating charge of high explosive and distance (which of course are related to overpressure, even if overpressure is not a part of the calculation). The British Explosive Safety Distance formula is an example that can be used to derive the ACR for B damage as a function of quantity of explosive:

$$R_B = \frac{5.6Q^{1/3}}{\left[1+\left(\frac{3175}{Q}\right)^2\right]^{1/6}}$$

where R_B is the ACR (metres) for B damage and Q is the quantity of explosive (kg). R_A, R_{Cb}, R_{Ca} and R_D can be expressed in terms of R_B:

ACR for	A damage is	0.675 R_B
"	B	1.0 R_B
"	Cb	1.74 R_B
"	Ca	5 R_B
"	D	10 R_B

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The distance up to which about 90% of glass is broken in ordinary houses is 5.0 R_B; for 50% incidence of breakage it is 10 R_B, and for 5%, is 20 R_B.

Although this assumes implicitly that the form of scaling is the same for all the charge weights in the data, the formula gives figures for B damage which compare well with WW II and accident data.

From a combination of world-wide accident data for explosions up to 2.4 kT in quantity plus some wartime data, Jarrett (1968) showed that the distance for the various categories of damage to the average British dwelling house could be closely approximated by the following formula:

$$R = \frac{kW^{1/3}}{\left[1+\left(\frac{7000}{W}\right)^2\right]^{1/6}}$$

where R is the distance in feet from W lb of explosive. k values for the standard damage categories are:

A	$k = 9.5$
B	$k = 14$
Cb	$k = 24$
Ca	$k = 70$
D	$k = 140$

'Quantity Distance' is another 'scaled' measure sometimes used as a measure of blast effect at distance R from W mass of explosive.

$$QD = \frac{R}{W^{1/3}}$$

If an explosion causes a shock wave of classical form, damage can be predicted from a given overpressure or deduced from a calculated overpressure, QD or k value, if the charge weight and distance are known. However, the mechanisms by which pressure waves of non-classical shape from VCEs damage buildings (and thus, the people within them) are different from those associated with TNT. Consequently, we cannot rely on unqualified analogies for quite different situations.

Raw data on damage to brick buildings at Hiroshima and Nagasaki (Hadjipavlou and Carr-Hill 1986) are not very useful, since Japanese house construction was very different to that of UK houses. However, data were available were for different types of industrial property. Hadjipavlou and Carr-Hill were able to extrapolate these data to apply to 9 inch, 11 inch cavity, 10.5 inch cavity (more modern) and 13 inch brick houses. Note that the findings were for high yields - duration of overpressure of about 1 second. Many types of brick houses, all with front face normal to the shock wave direction, were also exposed to blast from explosions of 1 kT upwards in tests in the USA. Details of damage are given in Chapter 3 of Hadjipavlou and Carr-Hill; many of the houses differed in construction from British ones,

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but in one test - DIRECT COURSE in 1983 - a pair of semi-detached houses built approximately to modern UK standards, suffered about A damage at 7.8 psi from the explosion of 609 tons of ANFO. A similar house exposed to about the same pressure from an 8 kT nuclear equivalent explosion suffered similar damage at the MINOR SCALE test, 1985. Note that this is about half the overpressure for the ACR for A damage from V1 and V2 bombings - an effect of the greater duration and impulse of the shock wave from these tests.

Regarding wood-framed housing, Hadjipavlou and Carr-Hill (1986) from analysis of Japanese multi-storey houses give 50% severe and moderate damage at 2.6 psi and 2 psi respectively. Tests on a mixture of full scale single and multi-storey wood frame buildings led to a prediction of severe and moderate damage at 2.2 and 1.4 psi respectively (Carr- Hill *et al* 1997). These are considerably lower figures than for brick house damage from similar yields (i.e. long-duration shock waves).

Other tests provided useful data on failure of individual components of brick houses. Pickering and Bockholt, 1971, in Hadjipavlou and Carr-Hill, used these to give estimates for pressures at which such components fail for US houses.

Details of shock tube tests on brick panels indicated that the failure pressures might be somewhat lower than those derived from war data. Hadjipavlou and Carr-Hill describe static load tests, and it is worth noting that the load to cause cracking, before failure can commence, is at least 3 psi for 9 inch brick. Failure does not take place until deflection reaches about half the wall thickness.

For WW II data, the houses would have been randomly orientated, and often shielded by other buildings. The shielding effects mean that overpressures to produce B damage derived from tests on isolated houses and brick panels might be up to 2 psi lower than those from war data (especially with high housing density). Random orientation will, on average, reduce the front face loading relative to the "normal" case (see graphs on page 123, Glasstone and Dolan, 1980). Hence, combining the two effects, B damage could occur at more than 2 psi lower for tests than for war data.

As a general rule, the overpressures generated at a distance from a VCE rise and fall much more slowly than they would for a TNT explosion, with a longer overall duration. This means walls are much more likely to be *pushed over* by overpressures which just exceed their elastic limits, because of the longer duration of the load. Moreover, the longer duration of the overpressures makes them more likely to collapse enclosed buildings. The comparative severity of hazard therefore depends on the physical characteristics of the component or building at risk. Close to a VCE, there is a greater risk of dynamic pressure damage - some strictly due to flow from the explosion, rather than the overpressure.

The loading on houses from a slowly rising pressure wave is likely to be notably different, since large reflected overpressures will not be generated. Consequently, loadings experienced by the front wall will simply be those of the incident overpressures themselves. An example of the possible effect of these lower reflected pressures would be that of glass on a wall facing an explosion, which might fail if exposed to a 1psi loading. Hence a classical shock wave of amplitude 0.5 psi would probably cause

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failure. However, a slowly rising pressure wave (for example from a VCE) would require an amplitude of 1 psi to cause failure. This phenomenon would also mean that "room filling", which only starts once the glass has broken, would start only once the incident overpressure had risen to 1 psi, whereas with a classical shock wave the room would start to fill at only 0.5 psi overpressure. The absence of reflected overpressures could also have a notable effect on the failure of the walls of buildings.

Without proper calculation (e.g. using the Rempel method) it is difficult to define the form of this filling, but it is estimated that the net loading on the front wall, because of room filling, would be approximately half the incident pressure. Hence, the wall elastic limit of about 3 psi would not be reached until the incident pressure reached 6 psi, i.e., the wall would not start to fail until this pressure. Whether failure occurred would be determined by the net impulse from that time; a peak overpressure of up to 12 psi might be required to cause this. However, the side walls would experience approximately the same loading as the front wall - hence the side walls might collapse at the same time as the front one, i.e., A and B damage start to occur at the same pressure.

Cates (1991) asserted that for most structures, the damage caused by the blast from a VCE would be less than that for a TNT blast of the same overpressure, so the use of TNT damage data would generally be conservative. However, he described experimental data on overpressure and flow from VCEs as still inadequate, although he was convinced that there were *'now fairly convincing theoretical models for the damage caused (to buildings) by any given flow and overpressure.'*

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4.3 Building damage and mortality data

Data on conventional bombs in WW II (Hadjipavlou & Carr-Hill 1986) showed that for low yields (below 1 ton), casualties in brick houses were caused principally by secondary casualty mechanisms - falling and flying debris. Falling debris is a more important mechanism than flying debris for circumstances in which the population has been warned, whilst the inverse is true for cases where there is no warning.

However, it must be noted that a large proportion of deaths due to falling debris arise from burial by debris in A damaged (almost completely demolished) houses. This proportion is dependent on the efficiency of rescue.

Fatalities in A damaged houses seem to be at least 31% of the population, if warned, and at least 54% of the population, if not warned. This is for a short duration overpressure of about 20 psi. Carr-Hill *et al* (1997) extrapolated WW II conventional bomb data and compared with high yield data, to estimate the types of damage and casualties for intermediate yield explosions. For a 50 ton condensed phase explosion resulting in a classical shock wave, he predicted that A damage would occur at lower pressure (8 psi compared with up to 20 psi for 1 ton) and that casualties would, once again, be caused mainly by falling and flying debris, though the proportion due to falling debris would probably be larger than that with 1 ton. For a slow rising 'pressure wave' (about 100 ms to peak), he predicted that A damage could be expected to suddenly occur at an intermediate peak pressure (about 12 psi).

The small contribution of primary blast effects to casualties in WW II is shown in Table 8 under "Blast". This is not unexpected, since primary blast fatalities would only occur very close to the explosions, where other causes of death would predominate. There are two other factors which, even for a classical shock wave, reduce the importance of primary effects. Firstly, there may be some peak pressure attenuation inside a building depending on the area of the building apertures. Secondly, a more gradual rate of rise of pressure results in an increase in the body's tolerance to injurious effects (White *et al* 1961, 1965).The rate of pressure rise for a person in a room is expected to be more gradual than in free field (Hadjipavlou and Carr-Hill 1986). With a VCE, the pressure rise time is likely to be significantly longer than that for a classical shock wave, further reducing the contribution of the primary blast effects.

Regarding secondary effects, Table 8 shows causes of injury and death for air raid victims in the open and in dwellings. Leaving aside bomb fragments, note that the three major causes of death in dwellings are falling debris (46.1%), flying debris (16.3%) and falls (5.8%). Glass causes a mere 0.2% of deaths.

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Type of Exposure	Injuries	Bomb Fragments	Blast	Glass	Other Flying Debris	Falling Debris	Fall	Burns	Other Causes	Un-Known	**Total Injuries**	**Total Casualties**
All Circumstances	Fatal	19.7	1.8	0.4	16.0	36.0	9.5	3.8	1.3	11.6	**850**	**680**
	Hospital	13.7	0.2	6.2	24.2	34.5	13.8	1.5	4.8	1.0	**1,117**	**684**
	Total	16.3	0.9	3.7	20.6	35.2	11.9	2.5	3.3	5.6	**1,967**	**1,364**
In Dwellings	Fatal	14.1	2.4	0.2	16.3	46.1	5.8	2.7	1.8	10.5	**439**	**353**
	Hospital	4.7	0.2	10.6	19.5	45.4	11.7	1.2	5.8	0.8	**498**	**303**
	Total	9.1	1.3	5.8	18.0	45.7	8.9	1.9	3.9	5.3	**937**	**656**
In the Open	Fatal	38.5	1.3	0.0	17.6	10.9	13.5	4.4	1.3	12.5	**160**	**122**
	Hospital	32.8	0.2	2.7	32.6	7.3	19.0	1.1	3.1	1.1	**261**	**159**
	Total	34.9	0.6	1.7	26.9	8.7	16.9	2.4	2.4	5.5	**421**	**281**

Table 8: Causes of injuries in air raid victims

If casualties from bomb fragments are ignored, the total flying debris casualties become 19.2% of deaths and falling debris deaths 53.7% (Table 9). Note that these figures are for air raid casualties, which implies some warning. For V2 explosions, where there was no warning, *flying debris* becomes a more significant casualty mechanism than falling debris (Carr-Hill *et al* 1997).

Injuries	Blast	Glass	Other Flying Debris	Falling debris	Fall	Burns	Other causes	Unknown
Fatal	2.8	0.2	19.0	53.7	6.8	3.1	2.1	12.2
Hospital	0.2	11.1	20.5	47.6	12.3	1.3	6.1	0.8

Table 9: Causes of injury in air raids less those due to bomb fragments

Note the low contribution of glass to fatality, even though it caused many injuries. Most fatalities from flying debris were <u>not</u> from glass.

As regards mortality after building collapse in WW II, Ministry of Home Security data showed that a large percentage of casualties were buried for a time under debris in completely or partially demolished rooms, and that people in completely destroyed rooms were almost always buried for a long time. The percentage of deaths due to Crushes (14%) and Asphyxia (21%) in dwellings, shown in Table 10 (Hadjipavlou and Carr-Hill, 1986) give an indication of the importance of the link between duration of burial and fatality. Although of course some crushes would have caused immediate death,

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Circumstance of exposure	Gross injuries and amputations	Lacerations and penetrating wounds	Compound Fractures	Simple Fractures	Crush	Asphyxia	Other Types	Un-known	Total Injuries	Total Casualties
All	18	11	13	10	12	17	7	12	850	680
In the open	17.5	22	17.5	11	9	4	7	12	158	122
In dwellings	20	9	11	8	14	21	6	11	439	353

Table 10: Frequency (%) of different types of wound in fatal air raid casualties

the survival rate of those buried under debris but not killed immediately falls rapidly with the increasing time after burial (Table 11 from Hadjipavlou and Carr-Hill 1986). Hence, the fatality rate is significantly related to efficiency of rescue. This is supported by earthquake literature (see below).

Period before casualties released	Demolished Rooms	Partly demolished rooms	All rooms
6 to 29 minutes after burial	84	96	92
½ to 2 hours after burial	43	66	53
2 to 12 hours after burial	32	38	34

Table 11: Survival rates of buried casualties in relation to time of release & state of room

Pressure pulses from VCEs usually have a long rise time; Carr Hill *et al* (1997) predict that the falling debris casualties are likely to be similar to those for a classical shock wave created by low yield explosions (up to about 1 ton), for the same degree of house damage. However, the contribution of flying debris to casualties is harder to predict since:

(a) objects will be accelerated less severely by the arrival of a slow rising pressure wave than by an instantaneously rising shock wave, and

(b) for a given peak side-on overpressure, fragments of building components that fail will have a lower initial velocity, since they will receive their initial acceleration from an overpressure close to the component failure pressure, not the much higher reflected component which is likely with shock waves. However the velocity may be increased by the blast wind from a VCE, more than it would be by the blast wind associated with a short duration shock wave.

Blast waves accelerate the body. There are two separate mechanisms; with shock waves, the first is the initial acceleration from the loading acting on the body as the shock wave flows around it in the first few milliseconds. The second is the force on the body imparted by the blast wind (dynamic pressure). The blast wind effect is highly dependent on yield (duration of shock wave). Although regarded as a relatively insignificant cause of injury at low yields of the order of one ton of condensed explosives, the small but significant figures for mortality caused by "Fall" in WW II air raids in Tables 8 and 9 would suggest that translational injury can be a significant cause of death in buildings even with charges of half a ton.

For a classical shock wave from an intermediate yield, the initial acceleration is still important, but the drag or blast wind assumes a greater additional importance. Displacement mortality could then become significant at 15 psi for standing people. For a VCE pressure wave with a long rise time, there

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will be a lower, but not zero, initial acceleration; the blast wind may play a much greater part, depending on pulse shape.

Data relating casualties directly to house damage taken from Hadjipavlou and Carr-Hill is shown in Table 12, which relates casualties to the damage data given in Tables 5 and 6 for houses damaged by V1 bombs.

Grade	No. of houses	Total no. of casualties			No. of occupants	% of casualties		
		Killed	Serious	Light		Killed	Serious	Light
A	206	76	63	20	323	23.5	19.1	6.2
B	172	7	29	22	257	2.7	11.3	8.6
Cb	299	0	30	19	326	0	9.2	5.8
Ca	173	0	4	4	182	0	2.2	2.2
D	44	0	0	0	45	0	0	0

Table 12: Casualties from V1 bombs related to housing damage.

Note that fatalities were found principally in houses with type A damage, with a few in type B but none beyond, although serious injuries were found in the C categories. This finding is supported by Hewkin (1992) - cited by WS Atkins. Hewkin also referred to several major explosives accidents, in which no fatalities occurred at below a metric scaled distance of 6 (overpressure 4.5 psi) - about the outer limit of category B damage.

Note also that even in A damaged houses, a significant proportion of occupants were not even lightly injured.

4.4 Fatality in buildings collapsing from non-explosive causes.

In predicting the likely fatality of the occupants of buildings which collapse, many authors turn to earthquake data. This is superficially attractive, as it would seem to give a source for predicting casualties from building collapse alone, without the contribution of other blast effects such as flying debris or bodily translation. However, such data must be used with care, since construction methods in those countries subjected to major earthquakes are often sufficiently different from UK techniques to make a notable difference to casualty production. Also, pre-shocks may give warning, and make considerable differences to casualty patterns particularly in daylight hours, when many potential casualties may save themselves by running outdoors before the main shock.

Alexander (1985) investigated the widely held assumption that the ratio of mortality to morbidity (non-fatal injury) is about 1:3 in earthquake disasters. This ratio was found with severe earthquakes of Richter magnitude 6.5-7.4. This implies an association with severity of housing damage, but Alexander noted confounding factors such as: (a) the time of day - casualties are heavier, and of the 'in building' type at night, and (b) the lack of standardised definitions of 'injury' in reports from earthquakes. In a later review (Alexander, 1993) he reiterated the marked variation of ratios of death to injury, and that building collapse was the principal source of casualties. Death and injury rate vary by orders of magnitude, depending on time of day. This imposes an important caveat on assumptions by some

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authors from the field of explosion damage, who assume that the entire population are at home an indoors at any time (far better demographic data is to be found in 'The Green Book' - Van Den Bosch et al 1992). As regards the relationship between numbers of buildings destroyed and numbers of casualties, Alexander found a variation of from 1 to 45 for numbers of casualties per 100 buildings damaged, with a mean of 18. He also noted a rather more regular ratio of deaths to buildings destroyed, of 10-16 per 100 buildings suffering 'total or partial collapse' (i.e. one casualty per 6-10 buildings destroyed). Note that this is only a small proportion of the population who would have been in buildings at the time.

Noji *et al* (1990), and Armenian *et al* (1992), described the 1988 earthquake in Armenia. They found a death rate of 49.4% in those buried by collapsing buildings, and a high casualty rate overall (64.1%) for the population, who mostly lived in un-reinforced masonry structures which collapsed completely. High death rates were also noted in collapsed pre-cast concrete buildings - with many of the deaths in both types of buildings attributed to dust asphyxiation. Both types of construction produced large amounts of dust (the concrete used was of poor quality). This was a hazard very specific to that environment, much less likely to be found in UK buildings. The hazard of dust from low grade concrete was also noted by Kaneda (1994).

All authors emphasised the rising mortality in those trapped by collapsing building as time to rescue increased. A significant proportion of buried earthquake victims are not killed instantly and may be saved by prompt 'heavy rescue' (Olson & Olson 1987) - 41 out of 56 fatalities being described as 'potentially salvageable' if rescued promptly. In major earthquakes where there is widespread destruction of the infrastructure, rescue equipment may not be available for many days, thus boosting the mortality. In an isolated instance of an industrial VCE in the UK, facilities for efficient rescue and first class medical treatment would undoubtedly be readily available.

Risk assessment, and the identification of the causal mechanisms of fatal and non-fatal injuries is probably as difficult to define precisely in earthquakes as it is for VCEs. One point made clear by review of the literature is how inappropriate and misleading it can be to apply conclusions drawn from rural events, to predicting death rates in urban disasters.

The paper by Glass *et al* (1977) on earthquake injuries in a Guatemalan village is frequently quoted, since it gives further support to the supposition that the majority of deaths and injuries are caused by the collapse of man-made structures; 5% of the population were killed. However, in Glass' study, it was made clear that most deaths were caused by a very specific local mechanism - the fall of 60 pound poorly bonded adobe bricks onto the elderly and young children. Adults tended to survive this impact, and there were very few deaths in any age group in other houses made from light materials. Concrete is variously described as hazardous for producing physical injuries (in the Philippines, where quality may be poor - Roces *et al* 1992) and as a very safe building material when seismic standards are adhered to (Eberhart-Phillips 1994). Both make the point that void spaces in collapsed reinforced concrete buildings may permit survival to occur.

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Withers & Lees (1991) concluded from the literature that the ratio of deaths to homes destroyed in earthquakes could be taken as 1 in 117; they found it to be 1 in 140 for tornadoes. However, these are death rates resulting from one phenomenon - collapse of buildings - without the threat of all the other mechanisms (primary, secondary and tertiary) which would add to injury and mortality in buildings collapsing as a result of blast. Indeed, Withers & Lees found the ratio of deaths to homes destroyed to be much worse from their assessment of data from the London 'blitz' - 1 in 12.5, with a similar ratio for data from seven chemical and gas explosions - 1 in 14.

It can be seen from the examination of the earthquake literature that an assumption of fatality rates, (based upon building collapse alone) of 60-80% of occupants of UK buildings, cannot be sustained.

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5. Prediction of injury or fatality from first principles

5.1 Introduction

An alternative to models based on housing damage is to estimate overall probability of injury of death from models of the individual injury mechanisms; this approach is sometimes described as an *'ab initio'* method.

Methods to predict death or injury by individual mechanisms have been developed and described by numerous authors, the most widely read and cited being Glasstone & Dolan (1980), Baker (1983) and Lees (1996). Probit equations are given to predict the probability of each individual event at a given overpressure (inevitably relating to shock waves, and usually of nuclear duration), or charts from which the probability can be read off if the overpressure and/or impulse, scaled or unscaled, are known. The separate probabilities of death or injury from the different causes are then added to give a total probability of injury or mortality, with a correction factor for those 'killed twice'.

Leaving aside for the moment the problems of validity of such methods even when measured against quantitative historical data, caution should be exercised in applying them uncritically to the prediction of damage to structures or people from VCEs. VCEs can produce pressure waves with totally different shapes to those produced by condensed phase high explosives, nuclear weapons, or FAEs.

As Mercx *et al* stated, '*In spite of all these differences, the damage criteria live their own lives. Because they are applied in both risk analysis and damage analysis for all kinds of situations, loops are created for which the link to reality is difficult to distinguish. This is surely valid in situations where other than high explosive detonations are expected, for instance the chemical industry.*'

Physical effects such as the failure of glass windows, the formation of fragments swarms, or displacement distances and velocities of standing dummies can be predicted with some mathematical accuracy. Charts of empirical data or probit equations derived from the same data or from theoretical physics may be used. However, progressing from these predictions to quantitative predictions of injury or mortality, either generally or by specific causes, requires the introduction of quantitative 'casualty criteria'. Those most commonly used (for primary blast lung injury, glass fragment injury, skull fracture, blunt injury from missiles and translational injury), originate from a surprisingly small number of original papers by authors such as Fletcher, White, Richmond, Ahlers and Feinstein.

It is instructive to read the original papers critically and to note the cautions attached by the authors to extrapolating their findings to human situations. Unfortunately, these cautions rarely survive to secondary, tertiary or quaternary citation. For example, Feinstein's paper in 1971 is quoted in authoritative text books, with reproduction of graphs showing kill probabilities from debris impacts to head, limbs and abdomen. These are then used as a basis for probit equations and other precise calculations. However, Feinstein claimed no such authority. He made it clear that assumption and extrapolation were used widely in the development of casualty criteria, and that probability estimates

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were of 'limited value.' He ended with a plea *for 'an attempt to be made to verify the estimates made in conducting this study.'*

Similarly, Ahlers' (1969) graphs of fragment impact damage criteria (quantitative mortality and morbidity) are reproduced in Baker's (1983) textbook, *'as presented by Ahlers (1969)'*. However reading Ahlers' paper reveals that he did indeed present the graphs, but gave no supporting data or arguments. However, once the graphs have been 'passaged' through Baker and other authoritative texts, they acquire an authority which permits them to be re-worked into detailed probit equations and mathematical and computer models.

Fletcher *et al* (1980) discussed the possible injurious or lethal effects of glass fragments. Their assumptions and stated caveats about extrapolation to humans have also been 'passaged' through the literature to the extent that many authors now accept the concept that a glass fragment which will penetrate the skin and 1 cm or more beyond will produce a 'serious wound' with a 10% chance of mortality as a 'fact', upon which sophisticated quantitative models can be constructed. White (1961), also describing injury by glass, wrote *'Let it be quite clear that such criteria are very crude and only tentative'*.

It is hard to blame eminent authors who have fallen into the trap of building and presenting complex quantitative models based on flawed casualty criteria. Models which predict high fatality rates from flying glass seem intuitively correct to authors. However, few of the historical events we have presented (which show how very few deaths are caused by flying glass in reality) are discovered by orthodox literature searches, however conscientious. Added to this is the authority ascribed to the figures and graphs by the large numbers of eminent authors who repeat them. In addition, many of the original papers are difficult to obtain; many are only readily available in the US.

There is a great deal of casualty data in classified defence documents. In addition to classified sources, open papers by such authors as Bellamy (1984, 1986, 1992), Carey (1987), Cooper & Ryan (1990) provide casualty information. Bellamy and Carey use large amounts of detailed data from the Vietnam and other wars to reveal, for example, how unlikely the injuries to the limbs or abdomen produced by missiles of the characteristics shown in the graphs of Ahlers (1969) and Feinstein (1971) are to produce the probabilities of fatality predicted. Very few (if any) such hits to the limbs would cause mortality, let alone the results on the 90% fatality curve. Cooper and Ryan (1990) support this with both clinical data and the results of experimental studies on wound ballistics. Military missiles with far higher energies than those in Ahlers' and Feinstein's graphs will very rarely cause deaths if they strike limbs (assuming that good quality medical care is available within a reasonable time). Only in a medieval, or post-nuclear scenario, could deaths be expected, principally from infection of untreated wounds.

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5.2 Skull fractures and mortality

Atkins use the assumption that any skull fracture will be associated with a 10% risk of mortality. Gurdijan *et al* 's study in 1949 using intact human cadaver heads is one of the cited authorities, but these authors note that *'there is no direct correlation between the severity of cerebral damage and linear skull fracture; that is, a fatality may result due to concussion without any skull fracture occurring. It is also true, however, that skull fracture may occur without any damage to the brain.'* Indeed, under some circumstances the skull may be fractured without even a transient loss of consciousness. Only very rarely is a skull fracture itself a cause of death; fatality is usually due to brain injury, and the skull fracture is a (rather inconsistent) marker of the severity of the mechanism causing the injury.

Thus, fatality may be the consequence of a head injury producing a skull fracture, but a skull fracture is by no means an invariable finding with severe brain injury. In civilian trauma practice, patients with a skull fracture are assigned a risk of developing an intracranial haematoma or other serious brain injury ranging from 1 in 45 (Gomez *et al* 1996) through 1 in 20 (Murshid 1994) to 1 in 10 (Servadei 1988, Johnstone *et al* 1996). Servadei makes the point that advances in neurosurgery and the general management of head injuries mean that many intracranial haematomas, recognised early, can be treated successfully without mortality and morbidity. They are no longer inevitably fatal, as seems to be tacitly assumed in papers from the 1940-1960s. This was by no means an unreasonable assumption in the context of nuclear tests and a post-nuclear scenario with mass casualties and severely limited medical services. Ersahin's series in 1992 gave an overall mortality of 10% of those with intracranial haematomas - i.e. a very small percentage of those with skull fractures.

Clinical series such as those cited above address those who survive to reach hospital, and so take no account of those who die at the scene of an accident from head injuries. Skull fractures typically may be found in 51% of those who die in terrorist bombings (Hill, 1979, Mellor & Cooper 1989), albeit usually as part of a pattern of multiple injuries. Brain injuries account for 60% of those who die. Skull fractures occur in one half of road traffic deaths and three quarters of fatalities with major head injuries (Shkrum *et al* 1994). Overall there are far more civilian trauma victims with head injuries, with or without skull fractures, who live to reach hospital than die at the scene of accidents. Of these, far fewer than 10% of those with skull fractures die, and death is far more likely to follow injuries with high energy transfer than low energy fractures of the vault of the skull or the type produced by Gurdijan's experiments. When the threshold for the production of such low energy skull vault fractures is used as an injury criterion, assigning a probability of 10% for fatality is notably over-pessimistic.

5.3 Review of major texts:

Glasstone & Dolan (1980), Baker (1983) and Lees (1996) are world authorities on different and overlapping aspects of explosions, and sources of extensive data used and quoted by numerous authors. All are cited by the WS Atkins reports, so a brief review of parts of their published work relevant to injury and fatality prediction is appropriate. All provide excellent descriptions of the processes involved in condensed phase explosions and their physical effects at short and long range.

Glasstone and Dolan also cover nuclear weapons, and Baker and Lees cover VCEs. Glasstone and Dolan are extensively quoted by the other two authors, and Baker is quoted extensively by Lees.

Glasstone and Dolan (1980) make the point that there is generally a lower probability of injury from direct overpressure effects inside a structure than at equivalent distances outside. This results from alterations in the pattern of the shock wave upon entering the structure - i.e. attenuation, as pointed out by Carr-Hill *et al* (1997). In discussing casualty figures from Hiroshima, they also point out that for survivors, the proportion of injuries from flying missiles and debris was smallest outdoors and largest in certain types of industrial buildings - an important point for injury, although no relationship to fatality is concluded. Nevertheless, this would seem to give circumstantial support to the WW II findings of flying debris being a predominant cause of death for the unwarned occupants of buildings, and that objects within the buildings become dangerous missiles.

Regarding non-radiation casualties in buildings, they relate overall casualties to the extent of structural damage as well as type of structure. They are honest about their assumptions, and do not attempt to produce or justify precise quantitations, attributing about half the mortality in reinforced concrete buildings close to explosion to radiation and half to '*overpressure, structural collapse, debris and whole body translation.*' They present a table that indicates a general correlation between structural damage and the frequency of casualties but emphasise that *'the numbers cannot be used to estimate casualties from the degree of structural damage'.*

Commenting elsewhere in the mechanisms of primary blast injury, they state that *'for wave fronts with sufficiently slow pressure rise.....quite high incident overpressures are tolerable.*' - this is probably a quote from one of White's papers (e.g. 1961, 1965) and is of possible relevance to the assumed reduced primary blast hazard from VCE pressure waves.

Glasstone and Dolan consider 'indirect blast injuries' (i.e. secondary and tertiary) at considerable length. Their qualitative comments which follow are much quoted, for example '*the wounding potential of blast debris depends on a number of factors; these include the impact (or striking) velocity, the angle at which impact occurs, and the size, shape, density, mass and nature of wounding objects.....consideration to portion of body involved in missile impact, and the events which may occur....namely, simple contusions and lacerations, or more serious penetrations, fractures and critical damage to organs.*'

For tertiary injury, *'..hazard depends mainly upon the time and distance over which acceleration and deceleration of the body occur. Injury is more likely to occur in the latter phase when the body strikes a solid object, e.g. a wall or the ground. The velocity which has been attained before impact is then significant. This is determined by...parameters of the blast wave ...as well as by the orientation of the body with respect to the direction of motion of the wave. The severity of the damage depends on the magnitude of the impact velocity, the properties of the impact surface, and the particular portion of the body which receives the impact -e.g. head, back, extremities, thoracic and abdominal organs, body wall, etc."*

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As regards displacement velocities, they consider together the relationship between blast parameters and objects of all size - i.e. from small pieces of glass to bodies. They emphasise that the significant parameters are the magnitude and duration of overpressure and the accompanying winds, as well as acceleration coefficient of object, gravity and distance travelled - the latter important because the velocity of an object can in theory increase with time and distance of travel until it reaches the velocity of the blast wind. In fact, large heavy objects gain velocity rather slowly and attain maximum velocity only after most of the blast wave has passed. In contrast, small light ones reach maximum velocity very quickly, often after only a small proportion of the blast wave has passed over them. Thus for small objects, maximum velocity depends largely on the effective peak overpressure, relatively insensitive to duration of overpressure and winds. Consequently, velocities attained by glass fragments from windows can be related fairly simply to overpressure. They present simple graphs for different glass thickness.

For tertiary (translational) injury, they refer to studies of displacement with anthropomorphic dummies, giving the example of a standing dummy at long duration 5 psi overpressure which reached a maximum velocity of 21 fps after 0.5 sec and a displacement of 9 feet. It travelled a further 13 feet before striking the ground and then slid/rolled another 9 feet. A prone dummy in the same circumstances was not moved. They also refer to studies in which animal cadavers were dropped from vehicles at up to 60 mph onto a flat surface to develop graphs of mass-corrected stopping distances. They note that the animals tended to assume a rolling position about long axis regardless of initial orientation; they remained low and bounced very little. They conclude that a person tumbling over a smooth surface might survive even quite high initial velocities, if head injury and flailing of limbs could be avoided. Note the implication - not made by Glasstone and Dolan - that in buildings, translated bodies are unlikely to have room to reach high velocities, except in large rooms. However, they are more likely to hit obstructions than to roll along an unobstructed surface.

They then discuss ***missile and displacement injury criteria***. They note that velocity criteria for skin penetration are not known with certainty, but that there is 'some reliable information' on the probability of penetration of the abdominal wall by glass - Table 13 (this will be an allusion to the work of Fletcher *et al* with dogs - which contains caveats about extrapolation to humans).

Mass (g)	1% prob.	50% prob.	99% prob.
0.1	235	410	730
0.5	160	275	485
1.0	140	245	430
10.0	115	180	355

Table 13: Velocity (fps) for stated probability of penetration of dogs' abdominal wall by glass fragments

This is a straightforward presentation of experimental data and derived statistics. however, the next table (see Table 14) - uses some of the same figures to predict 'serious wounds'.

Effect	Impact Velocity - feet per second
Skin laceration:	
Threshold	50
Serious wounds:	
Threshold	100
50 percent	180
Near 100 percent	300

Table 14: Tentative criteria for indirect (secondary) blast effects for penetrating 10-gram glass fragments

Glasstone & Dolan acknowledge that *'a serious wound is arbitrarily defined as a laceration of skin with missile penetration into the tissue to a depth of 1 cm or more'*, (which in the light of military surgical research and clinical experience is grossly over-pessimistic - see the earlier discussion of the effects of glass in producing casualties in real accidental and terrorist explosions). Penetrations of skin and of 1 cm or more of tissue by glass are in fact extremely unlikely to be lethal, although they may cause many unpleasant and disabling injuries - particularly if the eyes are struck. The fact that a 10 gm glass fragment travelling at 300 fps is nearly 99% likely to penetrate the skin and the 1 cm of muscle comprising the dog's abdominal wall does not mean that there is an almost 100% guarantee of a serious injury with a 10% chance of mortality in humans (wherever it hits on the body). Even if a piece of glass penetrates the human abdominal wall, the chance of death resulting from it, if modern medical care is available within a few hours, is extremely low.

This use of the term 'serious injury' in this context (which originated in a very qualified form in the works of Fletcher and White), has deluded many authors into overestimating the potency of flying glass as a source of predicted mortality.

For blunt impact injury, Glasstone & Dolan acknowledge that little is known concerning the relationship between the mass and velocity of non-penetrating missiles that will cause injury after impact with the body. They make the point that *'studies with animals showed that fairly high missile velocities are required to produce lung haemorrhage, rib fractures and early mortality, but quantitative data for man are lacking'*. They acknowledge that there are no quantitative relationships for injury from blunt trauma around spine, kidney, lever, pelvis but *'it appears that a missile with a mass of 10 pounds striking the head at a velocity of about 15 feet per second or more can cause a skull fracture. For such missiles it is unlikely that a significant number of dangerous injuries will occur at impact velocities of less than 10 feet per second'*. This is probably derived from Gurdjian *et al* (1949). Glasstone and Dolan then offer the following table (Table 15) without further justification:

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Effects	Impact Velocity (fps)
Cerebral Concussion:	
Mostly "safe"	10
Threshold	15
Skull Fracture:	
Mostly "safe"	10
Threshold	13
Near 100 %	23

(this table is used by Glasstone and Dolan, and reproduced by Baker *et al*)

Table 15: Tentative criteria for indirect blast effects to head involving non-penetrating 10 pound missiles

They address the hazard from translational injury striking a hard flat perpendicular object (as opposed to falling onto a flat surface). *'From various data'* (sources not given) *'it is concluded that an impact velocity of 10 fps is unlikely to be associated with a significant number of serious injuries; between 10 and 20 fps some fatalities may occur if the head is involved and above 20 fps, depending on trauma to critical organs, the probability of serious and fatal injuries increase rapidly with increasing displacement velocity.'* This sounds 'reasonable' but no evidence is given. They then offer the following table (Table 16):

Effect	Impact Velocity(fps)
Skull Fracture:	
Mostly "safe"	10
Threshold	13
50%	18
Near 100 %	23
Total Body Impact:	
Mostly "safe"	10
Lethality Threshold	21
Lethality 50%	54
Lethality Near 100 %:	138

(this is also given, as 2 separate tables, in Baker *et al* 1983)

Table 16: Tentative criteria for indirect (tertiary) blast effects involving impact

No justification is given for the assumptions inherent in these predictive figures.

They then address human tolerance of decelerative tumbling during translation on open terrain: *'virtually no human experience for checking the validity of extrapolations from observations on animal cadavers'*. There follows, without a supporting argument: *'the initial velocities at which 1 and 50% of humans are expected to become casualties as a result of decelerative tumbling have been tentatively estimated to be 30 and 75 fps'*.

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Throughout, Glasstone and Dolan are very honest about the tentative nature of all these quantitative predictions - but when they are quoted as authorities by others, these caveats are often lost.

Baker *et al* (1983) cite references much more liberally in the text than do Glasstone and Dolan. They correctly divide ***effects of fragments on people*** into penetrating by small fragments and blunt trauma by large ones. They refer to standard civilian and military studies on wound ballistics and penetration criteria for various missiles. They refer to Glasstone's 1962 edition as an authority about probability of glass fragments penetrating the abdominal cavity (all this in fact derived from early work from Fletcher *et al* who emphasised the need for caution in extrapolating to humans in a way which their later user of the data do not). They rework various equations for skin penetrations, but draw no conclusions. They then address non-penetrating fragments, using the same tables (15 and 16 above) as Glasstone and Dolan, although they do cite his sources by name, albeit without any details of evidence.

Ahlers' two curves for personnel response to fragment impact (abdomen and limbs) and serious injury threshold are presented as authoritative (see earlier discussion). These curves are also found in Feinstein (1971), in which it is emphasised how many ASSUMPTIONS are being made, and a plea made for further work to attempt *'to verify the estimates made in conducting this study'*. These caveats do not survive into Baker *et al*, as illustrated by the confident assertion: *'the percentage next to a particular curve in figure 6.20* (our Figure 8 in Section 7) *denotes the percentage of people (for a large sample) that would die if subjected to any of the impact conditions detailed in the curve'.* This would suggest that, for example, a blow on the abdomen *or limbs* from a ~60 g fragment travelling at 60 m/s, or a 1 gm at 500 m/s, would give a 90% kill probability. Experience of military surgery and ballistics research does not support this at all - the probability of mortality would be very much lower, especially in the limbs. Any estimates based on this would be notably over-conservative.

Baker *et al* have a section on ***Damage Criteria for People,*** which makes reference to Department Of Defence (DOD) quantity-distance separation categories, and present a clear DOD table giving expected effects on people for various overpressures and quantity-distances. They present no evidence, and rather pessimistic figures for primary blast injury. They discuss primary blast effects in some detail, giving lung and eardrum injury criteria, and reproduce Bowen survival curves for man (redrawn for scaled pressure and scaled impulse); none of this is contentious.

Baker *et al* make the point that in a series of industrial injuries from explosions only 1 of 78 deaths was from blast - the isolated case was in a detonation. All the other deaths were from fire or fragments, or a combination of the two.

They then addressed head and body impact due to whole body displacement. Much of this is the same as in Glasstone (1962) - an earlier version of Glasstone & Dolan (1980) which is quoted extensively by Baker *et al*. They use many of Glasstone & Dolan's tables. Baker *et al* supply the sources for these - 1960-70s US Atomic Energy Commission papers (which are not readily available). Baker *et al* cite Baker's own work on a method to predict the blast incident overpressure and specific impulse which will translate human bodies and propel them at, for example, the critical velocities given in Glasstone's

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tables. This method models the standing human body as a cylinder with a length to diameter ratio of 5.5, and a drag coefficient of 1.3 (when standing). Four body masses are modelled - babies, children, men and women. After scaling for altitude, graphs predicting skull fracture or lethality for a range of scaled pressures and impulses at a given altitude are generated; these are remarkably precise considering the limited accuracy and tentative initial assumptions

Although Baker *et al* provide brief discussion of the effects of non-shock pressure pulses on structures, their section on industrial explosion risk assessment seems to assume TNT-like shapes of overpressures.

This is an excellent source book, providing the quantitative human injury criteria are treated with the critical scepticism which they deserve.

FH Lees (1996) book devotes 28 pages of fine print to injury to humans. Since the edition cited by Atkins, he has produced a model (Gilbert, Lees & Scilly 1994) not published openly entitled 'a model for the effects of a condensed phase explosion in a built up area.' This covers effects and scenarios, W.W.II damage, fireball, fragments, and injuries indoors and outdoors. It includes computer programs EXMOD and EXFRAG. A paper by Wither & Lees (1991) gives an indication of its approach. Note that this program also specifically covers injury from building damage to people close by (but outside) buildings damaged by blast. The 1991 paper by Withers & Lees (although principally addressing lethal effects of condensed phase explosives in built-up areas) includes a brief section on VCEs. In this, they mention that '*application of the approach described here to vapour cloud explosions is likely to be directed mainly...to the estimation of secondary deaths.....A principal feature of the adaptation used here to vapour cloud explosions would therefore be the different effects of such explosions on buildings*', but they do not elaborate further. We have not been able to review the Gilbert, Lees & Scilly model, although we know the organisation that uses the model.

Lees presents fragment formulae - for fragment generation, swarm density, size of target and number of fragments hitting target, very similar to those in Baker *et al.* He then moves on to broad causes of injury outdoors:

- primary blast to lungs and eardrums;
- whole body translation;
- fireball;
- missiles;
    - *primary fragments;*
    - *crater debris;*

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- *falling masonry and glass;*
- *flying glass.*

Primary fragments and crater debris are unlikely to be significant causes of injury in VCEs. For indoors, asphyxiating dust should be added to the list of causes of injury

Lees advocates using his models of injury for the various causes of injury, applying each in turn, to predict the overall risk of lethality for persons outdoors. He also has a model for those indoors, based on the correlation between category of housing damage and the probability of injury derived from approaches given below.

For those outdoors: Lees cites Glasstone and Dolan(1980) and Baker (1983) as sources of a large amount of information on specific explosion effects. He acknowledges the origins of data provided by the above, by Zuckerman, and by the Lovelace foundation work by Bowen, Fletcher, Richmond, White and others. He also refers to the correlations of explosion injury given in 'The Green Book' (Van den Bosch *et al.* 1992). He then treats the standard data for eardrum rupture in some detail, including probit equations (which he seems to prefer to Glasstone & Dolan's 50% probabilities and thresholds). He does the same for primary blast lung injury - quoting Glasstone & Dolan and also Bowen, Fletcher & Richmond and presenting their usual graphs and curves. He reproduces some of Baker's re-worked scaled curves. For bodily translation, he gives the same table with the same assumptions about velocity and lethality as Glasstone & Dolan - acknowledged (and with conversion to SI units). He refers to the 'centre of mass' translational injury model of Hadjipavlou and Carr-Hill (1986) which itself seems to be a refinement of Baker's model. He also refers to Baker's Pressure/Impulse graphs for translation and produces probit equations based upon these.

For those indoors: Rather than modelling by specific explosion injury causes, Lees says *'for the most part it is necessary to rely on the correlation of injury with damage to structures, principally housing'.* For these, he refers to the Green Book (Van den Bosch *et al*), Withers & Lees 1991, and his unpublished model. He notes that large number of indoor casualties are from crushing and asphyxiation (including dust), but acknowledges that these causes would be *'difficult to model by any means other than by correlation with structural damage.'*

5.4 Models based on housing damage

Lees cites his own papers (e.g. Withers & Lees 1991) for housing damage and associated fatalities from tornadoes, air raids, earthquakes, chemical and gas explosions. We have quoted this data above in section 3. He uses the standard housing damage categories A-D and Jarret's *k* values for them. He also subdivides category A into Ab and Aa, for complete and almost complete demolition respectively. The Gilbert, Lees & Scilly (1994) model gives P(k) and P(SI) and P(LI) for the different housing damage categories as shown in Table 17 (which has been abridged to show only probabilities of

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fatality for occupants) for a condensed phase explosion occurring at random and without warning, in a built up area.

Housing Category Damage	P(K) - probability of fatality
Ab	0.96
Aa	0.57
A	0.62
B	0.086
Cb	0.009
Ca	0
D	0

Table 17: Probabilities of death for different categories of housing damage (Lees)

Lees presents tables of WWII injury causes and proportions similar to those in Hadjipaviou and Carr-Hill (1986), from same sources. Lees, like these authors, notes the insignificance of flying glass as a cause of death.

He discusses an alternative to models based on housing damage for estimating the overall probability of injury from the individual modes. He notes that a model for crushing and asphyxiation is lacking; this makes it difficult to construct a satisfactory model with this approach. He also refers to a 'model based on total injury' from nuclear data - undoubtedly classified hence few details are disclosed. From this, he derives and presents complex predictive graphs, but unavoidably, without supporting evidence.

Lees addresses casualties from flying glass in detail, generating probit equations. He correlates glass breakage with overpressure and *Rb* distance. He cites Mainstone (1971), and also Fletcher's data from the Eskimo trials, and produces equations for fragment characteristics and behaviour for different glasses under different conditions.

He uses Glasstone as a source of injury criteria (see above for limitations) from glass fragments - with the same tables (and tacitly the same assumptions) for 'serious wounds'. He refers to the Green Book's (Van Den Bosch et al 1992) method for predicting fatality for a person standing behind a window. Apparently, the Gilbert, Lees & Scilly (1994) model can make fatal and non-fatal injury predictions for any potentially penetrating fragment, including glass.

Usefully, Lees refers to Harvey's 1979 report about the Flixborough explosion (a large VCE) to emphasise that although a large number of windows were broken, only one (minor) injury was sustained from flying glass. He asserts that '*There is ample justification for regarding as negligible the risk of injury from flying fragments of window glass for an explosion which gives a peak overpressure outside the building of 0.6 psi or less*' (i.e. D damage).

Lees treats penetrating fragments in considerable detail, using assumptions about injury criteria from the "Textbook of air armament" and incorporating them into various models. He also makes reference to COMPUTER MAN, a US DOD computer model with which CBD are familiar in the context of prediction of military ballistic injury.

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Importantly, Lees acknowledges the effects of advances in medicine. He halves the assumptions of mortality from some W.W.II criteria - especially for limb injury. He refers to them, very correctly, as 'arbitrary.'

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6. The Atkins model

6.1 Objective of the Atkins model

The objective of the Atkins model is clearly stated in their reports:

"*The overall objective of this project is to develop a procedure for assessing the vulnerability of occupants of different types of buildings subject to overpressures produced from vapour cloud explosions. This requires the failure sequence of a building subject to increasing blast loads to be determined and the effect on people within the building of either debris generated by the blast load striking them or partial/total collapse of the load bearing structure to be determined.*"

WS Atkins - Phases 2 & 3 report, July 1996.

6.2 Overview of the Atkins approach

Two main approaches to estimating casualty or fatality rates from explosions are in general use:

(i) 'semi-empirical' or 'historical' methods which rely on scaling the casualty statistics from known explosive incidents;

(ii) methods which rely on the ability to model the relevant physical effects and injury mechanisms mathematically and then use casualty criteria to produce injury and/or mortality figures - an '*ab initio*' approach.

Both methods have drawbacks - inadequately detailed statistics for the semi-empirical methods, and inadequate casualty criteria for the methods developed from first principles. Faulty initial assumptions embodied in some casualty criteria have been forgotten or compounded when other authors have used them (or developed them further) leaving the criteria seriously flawed. These flaws usually lead to over-pessimistic predictions of death or serious injury. Some authors (e.g. Hadjipavlou & Carr-Hill 1986) advocate using both types of methods to provide a 'best estimate'.

The WS Atkins model uses the second of the two approaches outlined above - development of models from first principles (*ab initio* approach). Its 'general procedure' is shown in figure 6 (figure 1.1, page 5 of Jeffries *et al* 1997).

The methodology aims to derive generic fatality probability functions for a number of different building types, based on the primary structural characteristics of the buildings.

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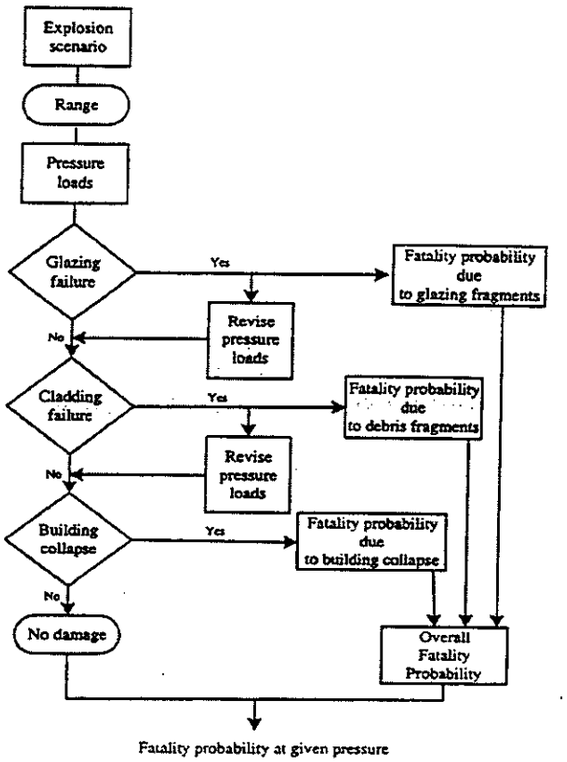

Figure 6: WS Atkins' model 'General Procedure' (from Jeffries et al, 1997)

The generic building types defined are the types typical of urban residential and commercial areas, with high occupancy rates, such as *'housing, offices, retail and leisure developments, schools and hospitals.'* Worked examples concentrate on two types - a typical brick-built semi-detached house and a reinforced concrete framed office building, with variations of construction techniques, dimensions, glazing characteristics and orientations.

The TNO 'multi-energy method' (see Van Den Berg 1985 cited by WS Atkins and the more recent Van Den Berg & Lannoy 1993) is then used to predict maximum overpressure, pulse shapes and durations at given ranges.

The structural loads generated by the blast waves are then considered, and the consequent dynamic response of the building predicted (using a non-linear single degree of freedom method). The calculated capacities of various structural components under dynamic loadings have been compared with historical and experimental data 'where available.'

The overall building response and failure of various components is then assessed, and the probability of fatality of the building occupants derived, based on the individual effects of:

glazing failure,

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- cladding failure;
- building collapse.

Note that the possibility or probability of death from the following causes is not addressed by the model:

- flying debris originating outside the building;
- translational injury within the building;
- burns.

Similarly, primary blast injury is not addressed - there seems to be a tacit assumption that this need not be considered in buildings separated from a petrochemical process plant by a safety separation zone. This assumption should be correct under almost all imaginable circumstances; a possible exception is the escape of a large vapour cloud and its movement by winds as far as a residential area before ignition. Also, primary blast injury could be a factor in control or office buildings on site, if engulfed in the cloud of a VCE.

Discussion of the Methodology in the Atkins' papers (1996 and 1997) includes the development of probit equations, with fatality probabilities finally expressed in the form of pressure-impulse curves (Figure 7).

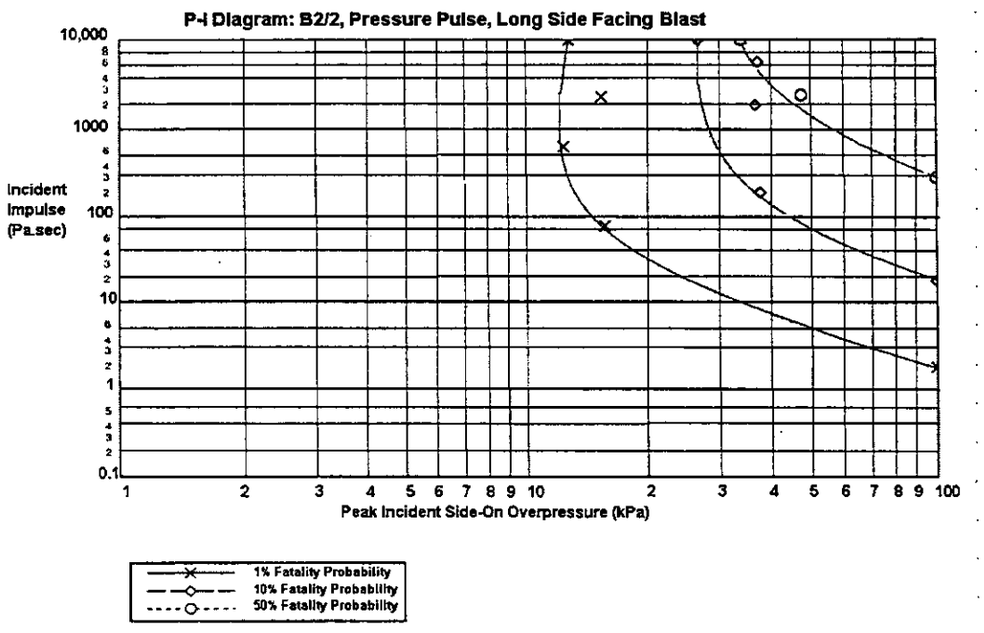

Figure 7: Fatality probability for impulse and incident overpressure (from Jeffries et al, 1997)

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7. Review of the Atkins approach

7.1 Introduction

This section details the findings of CBD's review of some aspects of the Atkins mathematical model. Our assessment of Atkins' methodology is made in the light of the preceding review of available information. The specific questions that CBD were asked to address were

(i) Does the Atkins methodology cover all the relevant injury types, mechanisms and conditional probabilities?

(ii) Does the methodology use the most appropriate available injury criteria to determine the conditional probabilities?

7.2 Injury types

The Atkins model includes some injury types that are considered to be important in relation to vapour cloud explosions. Other injury types are included that are not considered (by CBD) to present a significant risk of fatality. Some potentially significant types of injury are omitted from the model.

The Atkins methodology (Figure 6) addresses what are probably the two most important causes of fatality in buildings. These are:

- fatality due to building collapse;
- fatality due to debris fragments.

The methodology covers a third possible cause - fatality due to glazing fragments - which is predicted to be a significant cause of fatality in most models developed from injury criteria. However, far from providing supporting data, casualty figures from all types of war and peace time explosions show that **flying glass is a negligible cause of fatality**.

The Atkins methodology does not cover several other potential causes of significant mortality. These are:

- flying debris originating from sources outside and apart from the building (i.e. not building cladding failure);
- tertiary blast (translational injury) within buildings;
- burns - buildings do not necessarily provide protection from burns, burns are unlikely but may occur under certain circumstances,

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- primary blast lung injury - although we accept that this is not likely to be a notable contributor to fatalities.

7.3 Injury criteria

The Atkins methodology uses some of the best injury criteria available in the world literature, but these criteria are flawed and they render the methodology inaccurate.

Atkins have chosen the path of an '*ab initio*' predictive methodology for prediction of fatality within buildings, rather than an empirical methodology from historical data. For the injury mechanisms they have considered, they have used injury/fatality criteria from recent editions of authoritative sources. Their method is to consider a single building (or a number of buildings individually), and to predict the effects of a blast wave and the consequent casualty generation within from any failure of its components, using each of their three mechanisms of injury.

It is not part of our task to assess the methodology for predicting detailed building damage. Atkins have obviously considered the differences between a condensed phase explosion and a VCE very thoroughly, particularly with reference to the very different (and variable) overpressure/time profiles of the blast waves produced by VCEs. Their choice of the TNO multi-energy method to predict the characteristics of blast waves at given distances from a VCE is appropriate; this method is already well known to the HSE Major Hazard Assessment Group (see Cates 1991). They have also chosen to use a recognised single degree of freedom elasto-plastic model for the response of the building to the dynamic input (i.e. the predicted blast wave).

Our only comment on the multi-energy method is that although it is notably better than the TNT equivalence method, it suffers the drawback that it is usually necessary to make an arbitrary assumption about the explosion pressure (charge strength) and the combustion energy. This is usually done by arbitrarily choosing a conservative figure, and we recognise Atkins use of a range of combustion energies (Jeffries *et al* 1997, page 6). A number of competing computer models based on advanced numerical codes are available, such as FLACS (Bjerkevedt *et al* 1997)and several others (British Gas plc 1990). These claim to give better mathematical simulations of the events within the gas explosion in complex congested areas whose architecture can be specified in detail[5]. The models aim to give more realistic predictions of blast characteristics (including details of blast wave shapes) in both the near and far fields. Such developments should be assessed, since improved outputs might lead to better damage and fatality predictions. As Bjerkevedt *et al* (1997) state: '*do not spend a lot of time and effort estimating free field blast waves from gas explosions in scenarios where the gas explosion itself has not been analysed. You need to know the source strength in order to estimate the free field blast*'.

[5] However, such detail - eg that of pipework architecture - would not normally be made available in planning applications for evaluation by HSE.

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It should be noted that some of these programs claim to deal realistically with the blast wave diffraction, shielding and other effects around multiple rather than single buildings in the far field, and the near field.

Regarding the single degree of freedom model for building response, it should be noted that multi-degree of freedom models, finite element models and others are available, and that this is a rapidly changing field. Optimising prediction of building response and failure of components is also desirable, for optimum prediction of the consequent effects upon humans.

Progress is also being made in the area of modelling more precisely the loads received by structures subjected to different pulse shapes outside the 'congested region' of VCEs - see Cleaver *et al* (1997). In time, these may provide methods which are an improvement on the approximation of the pulse shape from a VCE to a triangle and shape factor (Atkins report, 1997).

In CBD's opinion, Atkins' assumption (Atkins report, 1997, page 11), that internal walls will not contribute to internal debris is not correct. Carr-Hill (1997) points out that injury hazard can start at the overpressure level of component failure, which may be below 2 psi for weak partitions. This is well above the pressure for glass failure, and would enter buildings with little attenuation if they had large aperture ratios. Glasstone and Dolan's (1980) category 'moderate damage' includes the 'blowing down' of partitions, and Hadjipavlou and Carr-Hill (1986) include the wrenching of partitions from fixings as one of the features found in 'Ca' damage. Large partition panels could be very hazardous missiles, particularly if striking edge on. They should not be ignored as an internal source of hazardous debris; different construction methods could make large differences to their significance as a potential fatality mechanism.

The methodology for predicting fragment generation from glazing failure and cladding failure contains a number of dubious but relatively unimportant assumptions. One of these is the correction factor of 1.5 on page 17 of their report which is based upon an experimental method for deducing the velocity of fragments from the depth of indentations in a witness plate. This method, respectable at the time of writing of the source paper, has fallen into disrepute for inaccuracy. Similarly, the assumption on page 18 that a fragment ceases to be hazardous once it falls below 0.5 metres above floor level would be disputed by the Texas City victims injured while lying in bed - the victim's position can alter vulnerability notably, for better or worse.

CBD agree with the assertion that for wall failure, the size of hazardous fragments will need to be assessed for each construction type. Jarrett (1968) pointed out (albeit for more energetic shock waves) that projectiles from brick walls usually consisted of not more than single whole bricks; however, reinforced concrete subjected to the same forces sometimes held together in lumps 4 feet square. The assumptions or 'corrections' at the bottom of page 19 of the Atkins report (1997), which reduce the velocities of large fragments of steel panels to 'remain appropriate' seem questionable, and worthy of further consideration and perhaps even experimental work

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CBD has commented on these aspects of the Atkins methodology (which are not strictly part of the CBD task) because sub-optimal modelling in these areas is likely to affect adversely any subsequent conclusions on fatality probabilities.

On the prediction of fatality probability, Atkins introduce the subject appropriately (page 20): '*There is considerable uncertainty in the prediction of human response to different types of trauma, and hence the calculation of the effects of an explosion is difficult. The area of human response is the subject of a further literature search.....*'

Glass fragments: CBD's review of historical events has shown that flying glass from explosions may causes numerous casualties but a negligible incidence of fatalities. The arguments in Atkins (1997) para. 2.5.1 move logically from stage to stage but the conclusions achieved are not representative of reality, because the casualty criteria drawn from accepted literature are flawed. This first appears in the leap of reasoning from predicting likelihood of skull fractures and skin penetrating wounds from glass fragments in dogs or sheep, to predicting fatalities in man. That a skull fracture has a 10% probability of causing fatality is over-pessimistic, but probably not by orders of magnitude. However, the assumption that a penetrating injury of a random site of the body (by a projectile with enough energy to penetrate 1 cm) has a 50% chance of causing a fatal injury, is over-pessimistic by orders of magnitude. Atkins do state that '*these values are subjective, however, and may be subject to revision as more data become available*'. Unfortunately, the pertinent 'more data' is the historical data showing that flying glass causes only a tiny fraction of explosion fatalities. The military combat epidemiological data shows that the chance of fatality from random hits by fragments with this limited degree of penetrating power, is very low.

The subsequent derivation of the 'fatality probability contours' with respect to distance behind windows is made unsound (despite the good physical predictions of fragment size, velocity and swarm density), by the flaws in the casualty criteria.

Probability of fatality arising from cladding impact: The sound approach to predict fragment mass and velocity is let down subsequently by poor casualty criteria. The source is Baker *et al* (1983); he presents graphs of fragment size and velocity (Figure 8) which were originally presented tentatively by Ahlers (1969) and by Feinstein (1971). These graphs were never designed to be authoritative bases for prediction of human fatality from blunt impacts to all body areas, and are over-pessimistic by orders of magnitude, particularly with regard to fatalities from hits on the limbs. The literature on combat casualty epidemiology supports this criticism.

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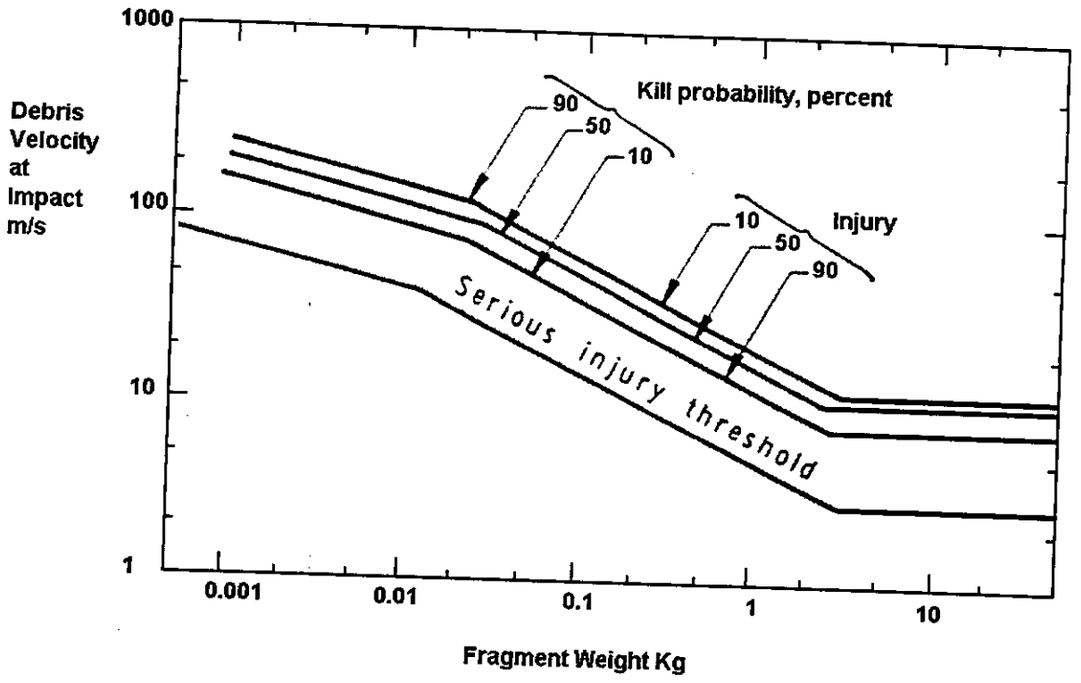

Figure 8: Personnel response to fragments impact (abdomen and limbs). From Ahlers, reproduced in Baker. Copied from Jeffries et al, (1997)

Probability of fatality arising from building collapse: The historical data providing figures for fatality from building collapse (from explosions and earthquakes) is reviewed in Section 4. Atkins' assumptions - and they make it clear that they are assumptions - of fatality probabilities of 60-80% are notably over-pessimistic. Table 12 indicates only a 23.5% incidence of deaths in the occupants of type A damaged houses in WWII - a fatality rate which would have been contributed to by all the other injurious aspects of explosions. Even the worst earthquake fatality figures are not as pessimistic as those given by Atkins, and the earthquake data was from incidents in which buildings had very adverse dust-generating features, and rescue was severely delayed by disruption of the infrastructure (e.g. the Armenian earthquake).

Overall fatality probability of building occupants: This section includes further assumptions about layout, occupancy and details of structure. These are required to apply the different parts of the methodology and combine them to produce the calculated overall fatality probability. The arguments which follow, although internally logical, are rendered unsound by the flaws in the casualty criteria used to generate the individual fatality probabilities. The 90% and 50% fatality contours behind the windows are particularly over-pessimistic.

P-I diagrams: The unsound injury criteria undermine the accuracy of the individual analyses.

Generic building calculations: Atkins provide a section on generic building calculations covering a range of building types Atkins do not take into account the internal components of structures '*except*

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where applicable as a barrier to debris', The range of overpressures considered by their graphs - up to 1 bar - are likely to be capable of tearing partitions from their fixings and transforming them, and other objects, into hazardous flying debris. For this reason, CBD recommend a review of the Atkins assumption. The 'correction' of arbitrarily reducing the size of panel sizes considered, to bring down the calculated velocity, also requires review. In the section on brick buildings, the assumption of 60% fatality from collapse is too pessimistic.

The predictive P-I diagrams have already been compromised by unsound casualty criteria. In addition, the assumptions on page 63 of Atkins (1997) about pulse shape effects on reflected pressures and front face loading are unsound. As Atkins rightly state, '*The characterisation of the partially shocked pulse with distance from a blast, and its interactions with a structure, is a problem which at the time of writing has not been assessed to a level which can be incorporated into this methodology*'. This is true, and the statement encompasses the problem considered earlier in this section when CBD recommended the review of current advanced computer models of the FLACS genre, as possible providers of less speculative waveform and overpressure information. It is also reflects why CBD recommended review of methods for more precisely predicting building response to such waveforms, thus hopefully removing some of the assumptions from this difficult area.

Comparisons: Atkins (1997) sought to validate their methodology, and provided a section on 'comparisons.' They note that '*rigorous validation of the methodology is difficult due to the scarcity of data*'. CBD have been able to acquire unclassified, but largely unknown government publications. We have also contacted authors.

Atkins cite Jarrett (1968) and reproduce his *k* value formula and values for the standard categories of housing damage. They then use their methodology to predict the probability of fatality in damage classes A and B, and find both of these to be over 80%. Here the lack of access to data such as that in Hadjipavlou and Carr-Hill (1986) and Carr-Hill et al (1997) proves critical - Atkins write that '*this seems to be a not unreasonable result*'. In fact, it is notably over-pessimistic, and the divergence of prediction by their methodology from historical fatality figures for this situation is even greater for class Cb damage, where they predict fatality probabilities between 14 and 40%. In fact, WWII fatality rates in Cb damaged houses were close to zero. Hadjipavlou & Carr-Hill (1986) present tables showing serious injuries but no deaths beyond B category damage (see also Table 12). Hewkin (1992) also commented that no fatalities occurred beyond class A or B damage in WWII data. Atkins refer to Hewkin's finding: '*this implies that our calculated fatality probabilities for category Cb above might be over-conservative.*'

Further discussion, particularly of Hewkin's paper, leads Atkins to conclude that with reference to fatality from flying glass, '*our assumptions are slightly over-conservative*' and that the assumptions '*most open to question in the assessment of glazing hazard are the assumed probabilities of a single hit causing a fatality.*' (i.e. 10% for a skull fracture and 50% for skin penetration). They suggest '*that further validation work might lead to a reduction of these values, although at present it is sufficient to note that they are probably conservative*'. CBD believe that the values for fatality from glass are so

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grossly over-conservative, and the problem so small in reality, that flying glass has little place in these models for fatalities, and that *'further validation work'* is not necessary.

In concluding their section on 'comparisons', Atkins regard their predictions for structural damage as *'in reasonable agreement with experience'*, which *'gives us confidence that the methodology is appropriate for use in risk assessment'*. They suggest two areas suitable for further investigation - fatality probabilities due to glazing hazard, and fatality probabilities from failed steel cladding. CBD shares their concern with the latter (and not the former). Their general conclusion is that *'the comparisons do show a reasonable level of agreement, with the predictions erring on the conservative side'*. The predictions certainly are over-conservative. Atkins over-estimate the level of agreement of their methodology with historical data.

Conclusions: Atkins recognise that *'detailed documentation of accidental and terrorist explosions could provide a useful insight into the distribution of injuries and fatalities'* ; CBD has been fortunate in accessing some of this data. They express concerns on the validity of methods for predicting the velocity of pieces of failed cladding of ductile materials such as steel; a concern that CBD shares. They speculate that their probability of fatality associated with being hit by flying glass is too high - this speculation is undoubtedly true in practice.

Further Work: CBD does not agree with the Atkins recommendation that the conditional probabilities relating to glazing impact, failure pressures and fragment masses and velocities for additional types of glazing merit further research. If *injury* is the key issue (and not *fatality*) further research would be fruitful.

We share their view of the importance of characterising the blast pulse itself - *'the characterisation of the pulse in its partially shocked state and the way in which such a pulse interacts with a structure is a primary source of uncertainty which is worth studying further'*. It would appear that better modelling tools are emerging - models such as FLACS and VEXDAM for truer waveform and overpressure outputs at different ranges, and computer models such as those alluded to by Cleaver *et al* (1997) for interaction with buildings.

A clarification of the behaviour of ductile (e.g. steel) cladding fragments would be of value, and CBD advocates a broader literature search and canvassing of experts.

Flying debris: Flying debris originating from sources outside and apart from the building (i.e. not building cladding failure) is not addressed in the model. Buildings do not invariably provide protection from large pieces of flying debris, particularly if these gain entry through windows. BLEVEs are a special case; very large metal fragments with great destructive power may fly for hundreds of metres, far beyond the major hazard range of blast. Buildings, sheds or other source of partial confinement may be entered by deflagrating clouds and then disrupted by the further rise in pressure consequent on confinement, producing large missiles of building material. Wooden 'utility poles' fail at about 5 psi

static overpressure (shocked) and 0.6 psi dynamic pressure, according to Glasstone and Dolan, and severely bent steel lamp standards were observed at Flixborough.

Tertiary blast injury within buildings: According to Glasstone and Dolan (1980),a 10 psi nuclear (long duration) shock wave is associated with a 2.2 psi dynamic pressure and a 294 mph wind. A 5 psi shock wave gives a 0.6 psi dynamic pressure and a 163 mph wind. If applied to a standing man, this loading would accelerate him to a velocity of about 21 fps in 0.5 seconds, and a displacement of about 9 feet. These pressures are well within the range considered by Atkins, although it is likely that they would only be experienced in site buildings rather than nearby residential areas. It should be noted that if the percentage of openings in the front wall of a building is more than 50%, the shock wave enters with minimal attenuation, and that the greater blast wind component likely in VCE pressure waves (as opposed to shock waves) at close-in range[6] or mid-distance will enhance the risk of displacement injury. The WWII data provides evidence that displacement contributes to fatalities.

Burns: Buildings do not necessarily provide protection from burns, however burns are not usually likely to contribute to fatalities from VCEs. Being engulfed in the cloud is likely to result in flash and flame burns; ignition of clothing significantly increases the probability of death by increasing burn area and burn depth.

The radiant heat from a BLEVE fireball can result in second degree burns in those exposed hundreds of metres away. Personnel engulfed in a fireball will inevitably die. House contents may also be ignited by radiant heat, since window glass stops only a proportion of the radiation spectrum emitted by such fireballs. Ignition of house contents may result in lethal flame burns, and/or smoke inhalation injury. In one example given by Baker (1983), the fireball from the BLEVE of one railway tank car containing 33,000 US gallons of hydrocarbon was seen to contact the earth initially at a radius of 200 feet, and radiant heat ignited combustible material up to a radius of about 1000 feet. Blast would have been a comparatively minor hazard at either of these ranges.

Primary blast injury: Under most VCE conditions, it would be very unusual to see primary blast lung injury, except within the boundaries of the cloud. Even within the boundaries, the victim would have to be close to one of the high pressure-generating confined/congested areas for a significant chance of serious lung injury. Note that the injury criteria for blast lung are all derived from work with classical shock waves and there is very little information in the literature about the effects of slow rising pulses, except a general agreement that they are less injurious for a given overpressure. White (1961) performed a few experiments with dogs, exposing them to sustained overpressures of up to 150 psi, with rise times of 30-150 ms. No fatalities occurred, and only minor lung injuries.

CBD knows of no quantitative data which would allow the prediction of fatalities with rise times other than instantaneous, nor of the effects of partially-shocked pulses or those with rise times of a few

[6] [6] Close-in range - peak overpressure >10 psi
Mid-distance 0.5-10 psi
Far- field < 0.5 psi

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milliseconds. This would be a possible area for further investigation, if it was thought that the likely exposure of personnel warranted it.

Primary blast injury should only contribute to fatalities outside a plant under unusual conditions, such as a cloud blown to engulf dwellings before ignition, and still able to produce significant deflagration pressures or detonation. Detonation of a cloud at a process site would present a notable blast lung mortality hazard to workers nearby, and those in hardened control buildings would be at risk if the resultant shock wave entered. Under these circumstances a shock wave would undergo multiple internal reflections, producing multiple pressure loads to personnel - a scenario known in the military sphere to increase the risk of primary blast injury.

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8. Conclusions

1. A review has been carried out of the WS Atkins methodology. The preliminary literature search has revealed hitherto unrecognised sources of detailed 'historic' casualty data, and has also revealed flaws in widely accepted injury criteria.

2. The two main approaches to predicting the probability of fatality for the occupants of buildings exposed to explosions are: (i) semi-empirical methods which rely on scaling the casualty data from historical explosions; (ii) methods which rely on the ability to model physical effects and injury mechanisms, and then use injury criteria to generate fatality probabilities (*ab initio* approach). Both methods have known drawbacks - inadequately detailed statistical data for the semi-empirical methods, and inadequate or misleading injury criteria for *ab initio* methods.

3. WS Atkins have chosen the latter methodology - prediction of effects from first principles. The physical events of vapour cloud explosions, effects on buildings, and the effects of specific injury mechanisms consequent to building failure on the occupants are predicted. The probability of fatality is derived from injury criteria.

4. The methodology uses the TNO multi-energy method to model the VCE. However, this model requires the user to specify two important parameters required for input - the explosion pressure (charge strength) and the combustion energy. The output is notably affected by the magnitude of the two parameters. It would appear from the literature that better methods are becoming available. However, some of these might be inappropriate for HSE's use because of their requirement for much more detailed data (for example on the specific arrangement of pipework at a site) than are normally available in planning applications.

5. The Atkins approach uses a single degree of freedom model to determine the response of individual buildings to blast waves. More sophisticated models may give better predictions.

6. The model cannot address interactions between blast waves and multiple adjacent buildings. These interactions are undoubtedly significant. Models are available which claim to be able to do this.

7. The assumption made in the Atkins model that internal walls do not contribute to hazardous debris is not sustainable, both from historical data and from known failure pressures.

8. The Atkins model covers the two injury mechanisms which have been shown by historical data to be the most important causes of fatality in occupants of buildings exposed to explosions:

   - building collapse;
   - flying debris.

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The method covers a third possible cause, fatality due to glazing fragments, but grossly overestimates its importance. Flying glass causes virtually no *fatalities* amongst the casualties of explosions, although it has been a major cause of *injuries* in many explosions.

9. The model does not cover four other potential causes of significant fatality in buildings. These are:

   - translational injury within buildings;
   - flying debris originating from sources outside and away from the building;
   - burns;
   - primary blast lung injury.

   Of these, translational injury is a significant potential cause of fatality (and certainly of injury) at the upper end of the range of overpressures considered by Atkins in their methodology. The probability of fatality from the other three mechanisms should be very low for most VCEs, but it is not zero.

10. The model uses the most widely accepted injury criteria available in the world literature for prediction of fatality from glass injury and for impact from flying debris. Unfortunately, these criteria are flawed and they render the subsequent interpretations unsound. This criticism arises from an examination of data from real events and by examining the original assumptions upon which the criteria were based.

11. Their injury criteria for predicting death from building collapse are over-pessimistic.

12. The flaws in the individual injury criteria will probably result in very inaccurate predictions of overall fatality probability of building occupants. Overall, these probabilities will be markedly over-conservative, despite the omission of some (lesser) potential causes of fatality.

13. Atkins' comparison of their predictions with historical data underestimates the disparity between those data and their predictions; they were not aware of the detailed data from WWII and terrorist bomb incidents.

14. Atkins' conclusion that they have developed a workable methodology for predicting the probability of fatality is unsound, in the light of data that has emerged subsequently and from a critical review of the assumptions and data supporting criteria. Their model and conclusions have been developed logically using injury criteria whose validity is unquestioned by major authorities in the field; the applicability of the criteria requires critical review.

15. Accidental and terrorist explosions typically produce large numbers of surviving injured casualties in relation to the number of casualties who die. Consequently, the human and financial cost of such explosions may be reflected poorly by predictive models which deal only with fatality

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9. Recommendations

1. The WS Atkins model is extremely conservative and should only be used where such a level of conservatism is appropriate. It is beyond our remit to judge whether use of this model is appropriate for HSE's purposes in connection with land use planning applications.

2. The model should be improved and the enhancements validated against all available historical data. New injury criteria will be required; it would probably be necessary to derive these as hybrids from historical and experimental data. Contributions from a number of specialist fields will be required - explosion and structural response modelling, combat epidemiology, military surgery etc.

3. There should be a thorough review and re-assessment of available and emerging computer models of vapour cloud explosions. CBD's review of these tools was simply an overview. The review should examine the prediction of shock and pressure wave characteristics such as pulse shape in the close-in, mid-distance and far-field zones.

4. Methods available to predict the effects of different pressure wave pulse shapes on structures and debris should also be reviewed - current practice is to approximate complex pulse shapes to simple triangles. These effects should be reviewed with particular reference to the acceleration of objects of all sizes (including humans) by both pressure and drag forces.

5. Further survey of recently identified historical data should be undertaken. It should aim to distinguish the contributions of all the different potential injury mechanisms to fatality in buildings exposed to explosion effects. The survey should start with a systematic review of the archives of Lord Zuckerman in Norwich.

6. The probability of injury and of its severity, as well as the probability of fatality, should be considered in future studies of casualty generation in buildings affected by blast.

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