

Blast Injury Science and Engineering

A Guide for Clinicians and
Researchers

Anthony M. J. Bull
Jon Clasper
Peter F. Mahoney
Editors

Alison H McGregor
Spyros D Masouros
Arul Ramasamy
Section Editors

Second Edition

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Foreword



We Will Remember Them.

A short walk from the central London campus of Imperial College lies Sloane Court East. This quiet, tree-lined residential street seems a world away from our busy university buildings and the work we do in its laboratories and classrooms to understand the complex effects of blast injury. Yet there is a very direct human connection. Anyone walking along Sloane Court East who cares to look can see two small memorial plaques, one inserted into the brickwork of a corner wall, and one set into the pavement. The plaques commemorate the deaths of 77 people who were killed at 07.47 am on 3rd July 1944, when a V1 rocket exploded at the north-western end of the street. Most of those who died were American service personnel. It remains the largest single loss of US military life on UK civilian soil in history. Despite this, the Sloane Court East explosion has been almost forgotten. Part of this process was deliberate. At the time, there was heavy press censorship in both Britain and the USA. The operation to liberate Europe, initiated on D-Day (6th June 1944), was less than a month old. The Allied advance was progressing, but at a slow pace. Neither government wanted their public to hear more bad news than absolutely necessary. Londoners were exhausted by sleepless nights spent dreading the onslaught of Nazi V1 flying bombs, whose destructive power was both brutal and inescapable.

The V1 rocket that appeared out of the morning haze over Sloane Court East on 3rd July carried 850 kg of high explosive in its warhead. Beneath its path were several six-by-six transport trucks loading up with US service per-

sonnel about to travel to their day's work at SHAEF offices in central London or to training camps outside the city. As it was designed to do, the rocket went silent a moment before gliding into its impact. These few seconds gave some of the soldiers and civilians just enough time to try to escape, but not enough for the men in the trucks to scramble out to join them. One young soldier remembered running around the corner of the street and finging himself to the ground at the moment of the explosion. He staggered to his feet, ears ringing, the air around him full of smoke and dust. Around him, other survivors were also able to stand and stumble back towards the scene of the blast. Although several of the buildings had been blown apart and there were fires breaking out in the rubble, many of the dead were lying in the open street, without crush wounds or other visible signs of injury. One witness remembered running through 20 or 30 bodies, desperately checking to see if any of them had a pulse, but their glassy eyes and dead weight told him that they were beyond his help.

At Sloane Court East, the worst killer had been completely invisible. V1 rocket explosive payloads produced huge blast waves that smashed out at least 400–600 yards in all directions. In the narrow street, this wave was confined and compressed by the solid stones of the buildings and tarmacadamed road surface, so its energy was exponentially increased, crashing through lighter, weaker structures. There was no blast crater where the bomb had landed, but bricks and masonry close by were pulverised into piles of dust. The sturdy US trucks and their loads of passengers were lifted into the air and slammed back on the ground, killing everyone inside. Pedestrians on the pavement were felled where they stood as the wave tore through their bodies. Fundamental blast physics explains the vacuum that always follows the initial blast wave that in turn generates a secondary wave. In Sloane Court East, one survivor described how it felt to directly experience such an effect where the building she was in “not only rocked, it did ground loops”. The secondary wave caused at least three houses and two blocks of apartments to collapse, trapping many people inside. A first aid post was set up, and survivors pulled from the ruins of the devastated street, some taking days to be rescued. Later, the grim business of identifying the dead from the mangled body parts taken to a nearby morgue was assigned to two young US officers, Lieutenants Riley and Byleen.¹ All the human witnesses to the horror of Sloane Court East are now long gone. Only its trees remain, planted as saplings in the pavements of the street in the years before the war, and somehow able to survive the blast wave's effects. They can still be seen today, grown as high as the buildings and apartment blocks that were rebuilt when peace came in 1945.

Because of other wars in our own time, our understanding of blast effects and injury has been transformed. Blast injury studies have become an established and productive part of our academic infrastructure at Imperial College London, as well as providing a globally influential model for effective multi-disciplinary co-operation across clinical, medical and bioengineering domains. We can model, predict and seek to mitigate the invisible wave and

¹Thank you to Alex Schneider, of www.londonmemorial.org, who has preserved the history of the Sloane Court East explosion.

its effects. Few mysteries remain. Wherever this work is done, it should be in the remembrance that blast injury always begins with a blast. Every blast event comes with the primary, secondary, tertiary and quaternary effects detailed and analysed so effectively in this volume. We should also be mindful of the other, less quantifiable effects: the horror, agony and fear just before the darkness and the silence. What for some is the point of wounding is for many others the point of dying. As we work to secure better ways for human beings to survive blast injury, we should also honour those beyond our help but never beyond our memory.

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September 2022

Emily Mayhew

Preface

There have been many advances in the field of blast injury research since the publication of the first edition of *Blast Injury Science and Engineering* in 2016. As such, we believed that now is the right time to collate the second edition, allowing us to expand on the content of the book and update several chapters with important new research and knowledge.

Many of the chapters in this second edition are built on the foundation of the chapters in the first edition, incorporating additional research to bring them up to date. We have also added several new chapters and included an entirely new section on Rehabilitation. We believe that the addition of the Rehabilitation section is crucial to such a resource as this, given that understanding of blast injuries, and importantly their long-term impact, does not stop at the point of wounding. People's lives are changed by their injuries and acknowledgement and collation of the breadth of work being undertaken in the field of rehabilitation is an important consideration.

The editors would like to thank all those that contributed to the second edition of the book. This includes more than 60 authors who have given their time and who have brought together expertise in science, engineering and medicine, from both military and civilian perspectives. We would also like to thank the new section editors who worked on this second edition of the book—Dr Spyros Masouros, Dr Arul Ramasamy and Professor Alison McGregor.

Finally, we would like to thank all the funders that have enabled the research which is discussed in this book. In particular, the editors would like to thank the Royal British Legion who have funded a significant amount of the research that has come from the authors based at Imperial College London.

We hope you enjoy this second edition of the *Blast Injury Science and Engineering* book.

London, UK
London, UK
London, UK

Anthony M. J. Bull
Jon Clasper
Peter F. Mahoney

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Part I

Basic Science and Engineering

Section Overview

1

Spyros D. Masouros

The multidisciplinary nature of blast injury, covering its pathophysiology, treatment, protection, and rehabilitation, requires an appreciation of a broad spectrum of topics in science and engineering. This section covers the science and engineering foundations required to follow the rest of the book. It introduces main principles, language, and techniques associated with the physics of

blast, the behaviour of materials, biomechanics, computational modelling, and biology and physiology. The objective is to bring the reader, irrespective of background, up to speed with the clinical, scientific, and engineering aspects required to follow comfortably the contents of this book.

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The Fundamentals of Blast Physics

2

William G. Proud

Abstract

Blast injury is an explosion effect and generally comes from the use of manufactured explosives. In some relatively rare occasions, the rupture of a compressed gas bottle or the breakage of a high-pressure storage or reaction vessel will result in blast injuries. There are many books on explosives that start with a historical summary of the discoveries and personalities involved before developing the theories and the quantitative measures used in explosive chemistry, physics and engineering. In this chapter, however, the aim is to present the reader with a timeline of events relevant to blast injury working from the point of activation of the initiator to the arrival of the blast wave at the human body or target. The steps will be presented in a simple, largely non-mathematical, way, introducing the basic concepts and placing the materials within the wider context. For those who wish for a more mathematically developed understanding, a selection of references is indicated for further study.

The Aims of this Chapter

1. Introduce some fundamental aspects of explosives and timescales
2. Provide an outline of how mines, blast and fragmentation work
3. Describe the energy release process and the efficiency of the process
4. Describe and distinguish between waves transmitting in solids, liquids and gases
5. Describe the range of fragment sizes and velocities
6. Provide an overview of shock and blast wave propagation
7. Outline how waves expand and interact with the surrounding environment

2.1 Explosives and Blast: A Kinetic Effect

Sound is a low magnitude stress wave. It propagates through air, causes a very minor change in the density of the air and moves at a fixed velocity. An **explosion** is a term used to describe the rapid expansion of gas, possibly from the rupture of a pressure vessel or a gas cylinder, the sudden vaporisation of a liquid, for example water exposed to hot metal, or by a rapid chemical reaction as seen in an explosive. The energy associated with a blast wave causes significant compression of the air through which it passes

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and the blast wave travels at a velocity faster than the speed of sound in air.

Explosives form part of a range of materials classified as '**energetic materials**'; other members of this class include propellants and pyrotechnics. The distinguishing feature of energetic materials compared to other materials is the very fast rate of energy release. This release rate and nature of the reaction products determine the use of the material.

The basic chemical components in an explosive are a fuel, an oxidiser and a material that allows a rapid ignition of reaction. In terms of total energy released, energetic materials are not particularly distinguished from other chemical reactions: petrol and butter release more energy per molecule when oxidised than tri-nitro toluene (TNT), probably the most famous explosive. This difference is that, while petrol needs to be mixed with air and then set alight, the explosive comes with the fuel and oxidiser intimately mixed, sometimes with both fuel and oxidiser present in the same molecule. The chemical or composition used gives information on intended application. Materials containing TNT, nitroglycerine, pentaerythritol tetranitrate (PETN), cyclotrimethylenetrinitramine (RDX) or tetrahexamine tetranitramine (HMX) are likely to be bulk explosives; these materials produce significant quantities of hot, high-pressure gas. Compositions using silver azide, lead azide, picric acid and the fulminates are sensitive to impact and flame, explode relatively easily, and so tend to be used in initiators, also called detonators; these materials are, however, very sensitive and so it would be unwise to use them as a main explosive charge.

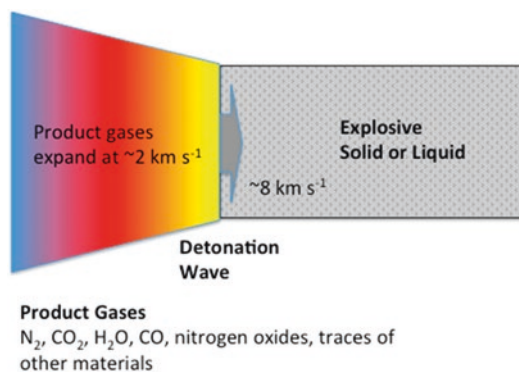


Fig. 2.1 Schematic of detonation process

High explosives, correctly called **high order explosives** include TNT, HMX, RDX and PETN often mixed with other chemicals to make the resulting explosive composition more stable, easier to process industrially or fit into cavities within a munition. When these materials detonate, they release their energy due to the passage of a reactive shock wave. A shock wave is a high-pressure stress and temperature pulse which moves through the material at supersonic speed. In the case of many compositions used in munitions, the shock wave consists of a thin, often sub-millimetre, region where the explosive turns from a solid or liquid into a hot, high-pressure gas (Fig. 2.1). The velocity of a detonation wave is of the order $5\text{--}8 \text{ km s}^{-1}$ and the energy release rate is of the order of Gigawatts; that is the same output as a large electrical plant over the time of a few microseconds. The pressure associated with detonation waves is many hundreds of thousands of atmospheres. The product gases expand quickly; a rule of thumb gives that the gas expands $\sim$ a quarter of the detonation velocity; it is effectively a 7200 km h^{-1} wind. It is not surprising that such aggressive energy release can be used to shatter and push fragments at high velocities.

Within the class of high explosives, there is a sub-division between so-called **ideal** and **non-ideal** explosives. Ideal explosives have very thin detonation-reaction zones where the reaction takes place on a sub-microsecond basis. Ideal explosives have a more pronounced shattering effect, or brisance, on materials placed in contact with them; this class of materials includes TNT. Non-ideal explosives have much thicker reaction zones and give out their energy over slightly longer timescales, up to several microseconds. The most widely used explosive in the world, Ammonium Nitrate: Fuel Oil (ANFO), falls into this class. The chemical make-up of ANFO results in much lower pressures of detonation, about a quarter of the pressure seen in high explosives, producing less shattering effect. ANFO, however, generates a lot of gas, which gives the mixture a lot of 'heave', the ability to lift and move the surrounding material. The low detonation pressure means this mix produces cracks in rocks which are then pushed open, heaved, by the detonation gas. These materials tend to be used in the mining and quarrying industry.

Low Order Explosives are materials that give out their energy as a result of rapid burning, called deflagration. This class of materials includes much of the materials often called gun-powders, where the reaction is due to the convective motion of pressurised hot gas moving through the powder bed causing particles to ignite. Here, the energy reaction rate is much lower of the order of a thousandth of that seen in high explosives. Again, to emphasise, the total energy output is similar to that of high explosives but the lower rate produces much lower pressures.

Both high and low explosives generally need a degree of mechanical **confinement** in order to detonate. A gramme of gun-powder on a bench will react quickly with a flash of light, a small fireball, some heat, but little other effect. The same quantity placed inside a sealed metal can, however, where the confinement allows the hot gases to stay close to the powder and pressure and temperature to build-up accelerating the reaction until the confinement shatters, produces an explosion or propels a bullet down a barrel.

Propellants are a wide group of materials where the reaction pressures are of the order of thousands of atmospheres and the reaction timescales are measured in milliseconds. These materials are used in rocket motors and to drive bullets or shells. In some cases, propellants, if confined or impacted at high velocity, may detonate. Missile motors may detonate if they overheat or if the product gas cannot vent quickly enough. As a group of materials, they can present a significant fire hazard and are sometimes used in improvised explosive systems.

Pyrotechnics are a wide range of materials including flares and obscurants. They do not pro-

duce high pressures but can generate significant heat and can be used to ignite explosives. They can be very sensitive to electrostatic discharge, but badly affected by moisture. Magnesium-Teflon-Viton (MTV) flares have been used to protect aircraft from heat-seeking missiles as they emit very strongly in the infra-red region but have no visible flame. As a class, they can produce severe burns to casualties and often are not easily extinguished by water or conventional fire extinguishers as they possess significant quantities of oxygen and energy within their composition.

2.2 Explosive Systems: The Explosive Train

Energetic materials are extensively used in munitions, both the type of energetic material and its function cover a wide range of masses and outputs. This can be seen clearly if we consider the amounts contained in a number of common munitions; a small arms round often has less than 1 g of propellant to drive the bullet, while a hand grenade would contain something of the order of a few tens of grammes to shatter and throw the casing, and a large anti-tank mine would contain up to 25 kg of high explosive. Given this array of systems, it is easiest to think of the explosive content within the munition in terms of the explosive train (Fig. 2.2), which indicates the basic prerequisites of an explosive munition system.

A variety of stimuli can be used to put the explosive train in motion such as standing on a mine, closing an electrical switch, activating a magnetic action, etc. These actions input energy into an ini-

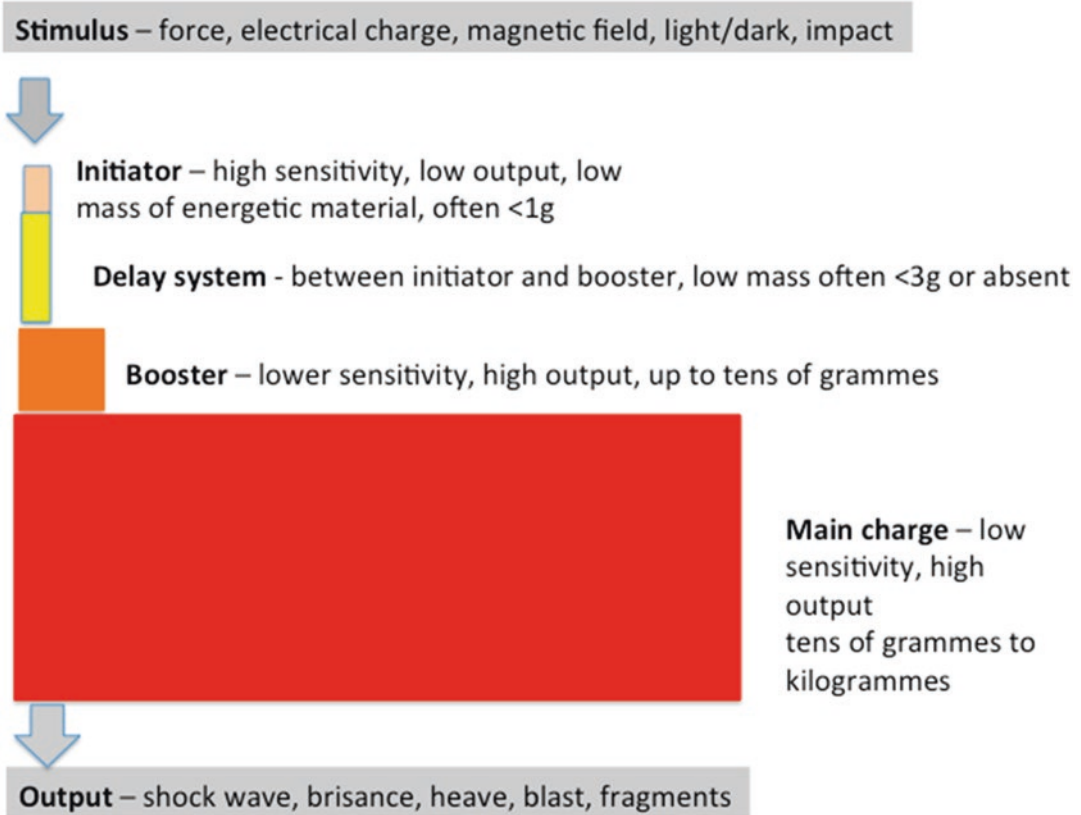


Fig. 2.2 The Explosive Train

tiator that contains a material that is highly sensitive, reacting when mildly crushed, impacted or heated. In anti-personnel mines, a simple design is based on a crush switch where applied pressure stabs a metal pin into a small metal thimble filled with a sensitive explosive. The main function of the initiator is to produce heat or a shock wave.

From the point of view of weapon-system design, it is useful to keep the amount of initiatory compound as low as practical, otherwise the weapon could become very sensitive to being dropped, shaken or transported. For many systems, a physical space or barrier exists between the initiator and the rest of the explosive system for the purposes of safety. This barrier is removed when the system is armed either manually or by an electrical/mechanical arming system. In the case of many bombs and missiles, the arming sequence occurs after the weapon has been launched to provide security to the user and the launch platform.

The heat or shock from the initiator is transmitted either along a delay system or directly into a booster charge. The function of the delay is to burn for a known period allowing time for other processes to occur such as throwing a grenade or allowing a small propellant charge to 'bounce' a mine into the air. Delays are important in quarrying and mining where exploding a set of explosive-filled boreholes in a sequence allows for more efficient material extraction.

The booster system consists of an explosive compound that is less sensitive than the initiatory compound but will detonate due to the heat of the shock wave from the initiator. The energy output of the booster is much higher than that of the detonator. The shock wave is then transmitted to the main charge.

The main explosive charge consists of a relatively low-sensitivity explosive composition that will detonate from the energy delivered by the

booster. The mass of such main charges is extremely variable, however, the output from the main charge can be defined in terms of the outputs.

These outputs include: (1) shock waves transmitted into the immediate environment around the explosive; (2) the shattering of surrounding material, such as a metal case; (3) the expansion of hot product gases violently accelerating the surrounding shattered material opening a gas-filled void in a structure; (4) the coupling of some of the explosive energy into the air, producing a blast wave; (5) the aggressive acceleration of fragments, shrapnel or target vehicles and people.

2.3 Energy Levels and Energy Distribution

To allow some generalisation, it is useful to consider the amount of energy output and the physical characteristics of the materials involved. One gramme of propellant will produce 1 kJ of energy. The temperature of explosive product gases can easily exceed 3000 K.

As gases are about a thousand times less dense than solids and liquids, the result of this is that 1 g of solid turns into 1 L of gas if that gas is at room temperature. The gas, however, is ten times hotter than room temperature (using the absolute, Kelvin temperature scale). This means that the 1 g of material turns into a gas that, if allowed to expand freely, would occupy 10 L. Alternatively, it would take 10,000 atm to keep the gas from expanding. This order of magnitude calculation for the less aggressive propellant materials shows the levels of force that are produced.

Of the energy that is released by the propellant, the proportion of the energy that goes into different processes is revealing. Again, a simple order of magnitude estimate indicates that 20–30% of the energy will go into the kinetic energy of the fragments, 60% into the kinetic energy and temperature of the explosive product gases, while the remaining 10–20% will be spread over a number of other effects, such as the blast wave, the energy required to fracture shell casings, the motion of the ground, etc.

2.4 Formation and Velocity of Fragments

Many explosive systems have a casing, usually of metal or plastic, often with features or inserts to form specific fragment shapes (see Chap. 8). Some systems have very thin casings; this is generally done to reduce the metal content or mass of the munition. Reducing the metal content makes landmines harder to detect—‘low-signature’—but also has the effect of slightly increasing the blast as less energy is used in fragmentation or acceleration of fragments. As many landmines are designed to maim rather than kill, reduction of metal content also assists in this.

The initial effect of the detonation wave is to send a shock wave into the casing which produces a violent acceleration of the casing. Figure 2.3 shows the velocity profile from the outer surface of a copper cylinder subject to loading from the explosive filling. On the right-hand side of this figure, a schematic of the process of acceleration is shown. This diagram considers the motion of the wall of a cylinder filled with explosive, as the explosive detonates: the horizontal axis represents distance and the vertical axis time. The detonation products send a shock wave into the cylinder from the inner surface to the outer surface; this is represented by the black line with an arrow on it. A wave reflection takes place at the outer surface, sending a release wave back into the casing, towards the inner surface. This in turn is reflected from the inner surface as a shock. As this back-and-forth wave reflection process takes place, each reflection represents the acceleration of the casing expanding in a series of steps. As the casing is accelerated outwards, it expands and becomes thinner. The diagram on the left also indicates the violence of this acceleration; the outer surface moves from rest to reach a velocity of $0.8 \text{ mm } \mu\text{s}^{-1}$ (corresponding to 800 ms^{-1}) within $5 \text{ } \mu\text{s}$. More detailed discussion of how this can be calculated can be found in the specialised texts of the explosives engineering community, detonation symposia and shock physics literature. The total distance moved by the casing within this very narrow time window was only 0.6 mm. Thus, the metal casing is subject to very violent acceleration; this causes fracture and fragmentation within the casing producing metal splinters moving at high velocity.

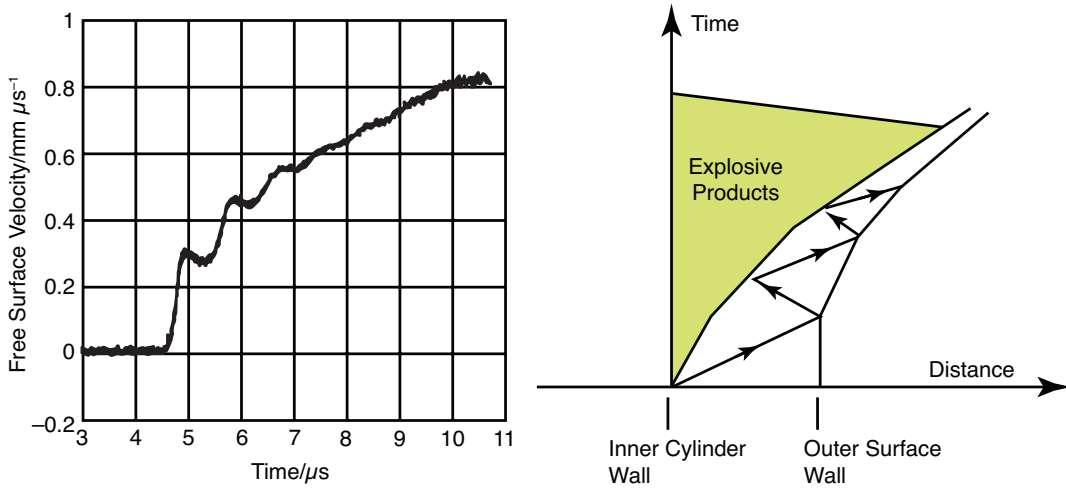


Fig. 2.3 Left: the velocity history of the outer surface of an explosively loaded metal cylinder. Right: a distance-time diagram of the wave processes taking place within the casing

The study of fragments and fragmentation took a major step forward during the Second World War (1939–1945) with significant scientific effort placed in the service of the militaries of industrialised nations. The two major studies are named after their main originators: Neville Mott and Ronald Gurney. The number and size of metal fragments from a casing were addressed by the Mott fragmentation criteria. This is a statistical model based on the idea of a rapidly expanding metal ring which contains imperfections. The imperfections form the basis of fractures which

eventually break the ring into fragments. As the ring breaks, the stress inside the resulting fragment reduces and further fragmentation does not occur. This model was developed and populated in a semi-empirical fashion where the results of theory and experiment were compared.

The result of the modelling and experiments was to produce a series of curves giving fragment-size distribution. An example is shown below, in Fig. 2.4, where a Mott calculation is compared to experimental data of fragment distribution from an iron bomb.

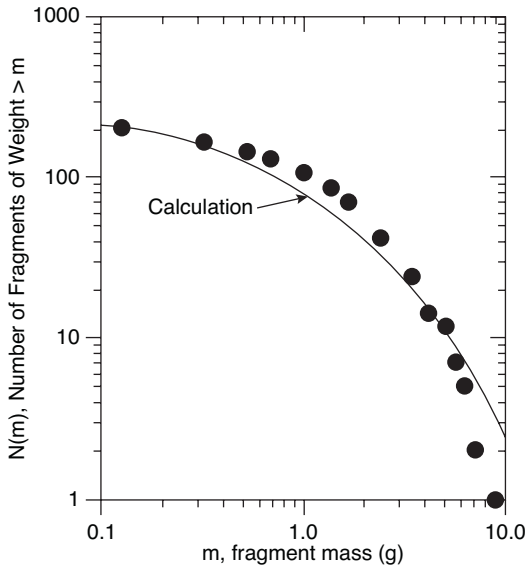


Fig. 2.4 Fragment distribution from an iron bomb [1]

The research of Gurney considered the balance of energy in the system; how much of the released energy would be captured by the metal casing, so predicting the expected fragment velocity. In the derivation of the velocity, the casing was assumed to remain intact during the acceleration process. The shape of the explosive charge and the casing has a major effect and this resulted in the production of a whole series of Gurney equations. In Eq. (2.1), below, the expression is for the velocities achieved by explosive loading of a cylinder

$$\frac{V}{\sqrt{2E}} = \left(\frac{M}{C} + \frac{1}{2} \right)^{-1/2} \quad (2.1)$$

where C is the mass of the explosive charge, M is the mass of the accelerated casing and V is the velocity of accelerated flyer after explosive detonation. The term $(2E)^{1/2}$ is the Gurney constant for the explosive; it has the same units as velocity and is sometimes called the Gurney velocity. Each explosive has a particular value of Gurney constant and accounts for the coupling between the energy of the detonation products and the energy deposited into the metal casing.

While the two approaches may seem contradictory, one assuming fragmentation and the

other an accelerated but intact material, using both approaches is useful due to the timescales of the initial acceleration and fragmentation. The energy delivery by the detonating material occurs very quickly giving the initial impulse, while fracture takes time and expansion to develop. Once the fractures have started to open, the product gases escape, potentially causing a fireball, but only producing a limited change on fragment velocity post-fracture. Overall, the two approaches have provided a reasonable and predictive approach to fragmentation and fragment velocity.

From this section, it can be seen that explosives produce violent fragmentation and acceleration: a large number of small fragments and much fewer large fragments, moving at velocities that range from several hundred to a few thousand of metres per second. These fragments can produce significant, life-threatening injury in themselves, irrespective of the blast wave associated with the explosive charge.

2.5 Shock and Stress Transmission

At this point on the timeline, the munition has detonated and a shock wave has passed through the casing, which is starting to move and fragment. In total time, a few tens to hundreds of microseconds has passed since the main charge started to detonate.

The next effect that needs to be considered is **the transmission of the stress waves between materials**: how does the detonation pressure transmit from the product gases into the surrounding material, soil or rock? what are the properties involved? what is the resulting velocity of material when it is subject to a stress wave?

In all cases of wave transmission, it is important to consider what the type of the wave is, what the magnitude of the wave is, what are the properties of the material through which it is travelling and what is the change in material properties across the interface.

2.5.1 Wave Type

Wave motion can be broadly defined into three classes: compression, tension and shear. Compressive waves are associated with positive stresses and pressures, tensile waves with negative stresses and pressures, while shear waves produce motion lateral to their direction of propagation. To think of the action of a lateral wave, consider a pack of cards placed on a table; if you press down on the top card and move it sideways, then the cards underneath will move sideways as well, however, each card does not move quite so much as the one above it; the resulting spreading of the deck of cards is the result of shear. Shear waves produce the same kind of motion in materials as seen in the card deck.

The velocity at which the stress wave moves changes with stress level. For solids with strength, at stress levels below that of the elastic strength, the velocity of the wave is the same as the speed of sound in the material. For stress pulses that are above the strength of the material, the compression of the material results in the wave speed being higher than that in the uncompressed material; this is the definition of a shock wave.

Waves that reduce the stress level are generally called tensile waves and are most commonly seen when a material is pulled. If the material is dropping from a shock-compressed state, then this wave is more correctly called a release fan. In most common materials, the shock velocity increases with stress, while the stress-reducing release waves move at increasingly slower velocities as the stress drops; this is a result of the change between the very aggressive shock loading and the relatively slower and milder release process. Thus, the release region spreads, or fans out, over a much wider region than the thin shock front, and is most often associated with a continuous decrease in stress to the ambient pressure state.

2.5.2 Magnitude of the Wave

The magnitude of the stress wave is defined in terms of its stress level. One factor that often leads to confusion in the field of stress propagation is the relationship between stress and velocity. The important thing here is to remember one of Newton's laws of motion—a **body will continue in a state of rest or motion until acted upon by an external force**. It is, therefore, perfectly possible to have a material, fragment, etc. moving at a high velocity under no external force and also possible to have a material under high pressure but not moving.

The basic equation to be defined is the relationship between stress, the volume through which it moves and the acceleration it produces in the material. The law to be considered here is conservation of momentum; the product of mass multiplied by velocity.

The definition of stress (σ) is force (F) divided by the area (A) it acts over.

$$\sigma = F / A \quad (2.2)$$

The mass (m) of the material that is affected by the passage of the wave is going to be the volume the stress wave has moved through multiplied by its density.

The volume (V) that the stress has swept through will be the area (A) multiplied by the velocity at which the wave moves (U_σ) over the time window we are interested in (δt). The density of the material is represented by ρ .

So the mass that has been accelerated will be

$$m = V \rho \quad (2.3)$$

and from the argument above

$$V = AU_\sigma \delta t \quad (2.4)$$

So the mass is

$$m = \rho AU_\sigma \delta t \quad (2.5)$$

The final step is to consider the acceleration and the final velocity obtained. Here, we use one of the fundamental equations representing the acceleration (a) produced by a force (F),

$$F = ma \quad (2.6)$$

where the acceleration (a) is the change in velocity of the material (δu_p), sometimes called the particle velocity, over the time window we are considering (δt).

$$a = \delta u_p / \delta t \quad (2.7)$$

Combining these terms to relate stress to change in velocity, we arrive at the equation

$$\sigma A = \rho A U_\sigma \delta t (\delta u_p / \delta t) \quad (2.8)$$

which simplifies to

$$\sigma = \rho U_\sigma \delta u_p \quad (2.9)$$

This is one of the fundamental equations in shock physics, one of the so-called Rankine–Hugoniot relations. The full set of these Rankine–Hugoniot relations can be found in the introductory texts by Meyers or Forbes [see further reading section].

The fundamental relationship here is that the change in velocity produced by a stress wave is

dependent on the density and the wave velocity of the transmitting material. The value of the density of the material multiplied by the wave speed is called the impedance (Z) of the material.

At low stress levels, the velocity at which a stress wave travels through a material is the same as the material's sound speed. At higher stresses, when a lot of force is applied as in an explosion, the velocity of the stress wave can be higher than the sound speed, a shock wave. As stated earlier, a detonation wave is a shock wave that is driven and supported by the energy release of the chemical reaction.

2.5.3 Impedance: A Property of the Material

In principle, the value of impedance for low stress levels is easy to calculate; it is the product of the density multiplied by the sound speed in the material. Table 2.1 contains the density, sound speeds and impedances of some common materials; air at 1 atm, water, iron, tungsten and Perspex®. These materials have been studied extensively and their properties are quite well known. The impedance of air changes strongly with pressure and is discussed in Sect. 2.6.1.

Table 2.1 Impedance, density and sound speed values for a range of materials

Material	Density/kg m ⁻³	Sound speed at 1 atm pressure/ms ⁻¹	Impedance/kg m ⁻² s ⁻¹
Tungsten	19,220	4030	77.4 × 10 ⁶
Iron	7850	3570	28.0 × 10 ⁶
Perspex®	1190	2600	3.09 × 10 ⁶
Water	1000	1500	1.50 × 10 ⁶
Air	1.292	343	4.43 × 10 ²

As the stress level in the wave increases, however, then other properties such as strength and compressibility become important. As the stress level increases, so does the amount of energy that is being deposited in the material; some of this will result in increasing the kinetic energy of the material while another part of the energy will result in the material being compressed and becoming hot. The exact mathematics of this situation is complex and beyond the space available in this brief chapter, however, we can outline some simple conceptual guidelines.

The strength of a material is its ability to resist distortion; this strength will be different in compression, shear or tension. Materials with high strength tend to have high sound speeds as a result. Metals, in general, have similar strengths in tension and compression, while rocks and ceramics are strong in compression but weak in tension. Granular materials such as sand have no tensile strength, but can have significant compressive strength. Given the three-dimensional jigsaw-like nature of sand, the more you press down on the sand the harder it is to move it sideways, in other words shear it.

Compressibility is the ability of a material to deform and is the inverse of strength. Highly compressible materials such as foams are often used to protect objects from impact; they do this because the energy of the impact is absorbed in locally distorting and compressing the material in the region of impact and not into increasing globally the kinetic energy of the foam. Sands, soils and granular materials absorb energy in a number of ways by grains deforming, and grains fracturing, the particles moving together to fill the pores. These mechanisms absorb energy and act to mitigate the shock or blast wave.

As the material compresses, its density will change and its sound speed will tend to increase. At some point, the amount of compression in the foam will result in the removal of the majority of the voids at which point the material will behave like a stronger, solid mass; there is a limit to energy absorption. Similarly, all materi-

als will have a yield point, where their yield strength is exceeded and they begin to deform and compress so there will be a change in how the energy in the stress pulse is deposited; more will go into temperature and into internal compression processes and less into velocity. In addition, time-dependent processes will also be occurring; the time for pores to collapse in foams and for particles to fracture in sands, so there will be a time dependence to the stress transmission.

The same issue of time dependence in the change of impedance, degradation of strength, and interplay between kinetic energy and compressibility occur in biological materials. The impedance of the material will change through the stress pulse and so the simple equations given should always be used with caution and to produce estimates.

2.5.4 Wave Transmission Across Interfaces

When a stress wave reaches an interface, it is the difference in the mechanical impedance of the materials which determines how much of the stress wave is transmitted and how much is reflected. By using conservation of momentum and the impedances of the materials, the amount of the stress transmitted and that reflected can be calculated and the **change in stress** in the materials calculated. The results of this is given in Eqs. (2.10) and (2.11)

$$T = 2Z_2 / (Z_1 + Z_2) \quad (2.10)$$

$$R = (Z_1 - Z_2) / (Z_1 + Z_2) \quad (2.11)$$

where T is the fraction of the stress transmitted, R is the fraction of the stress reflected, Z_1 is the impedance of the material through which the stress is originally transmitting and Z_2 is the material on the other side of the interface. Three situations are shown in Fig. 2.5b–d.

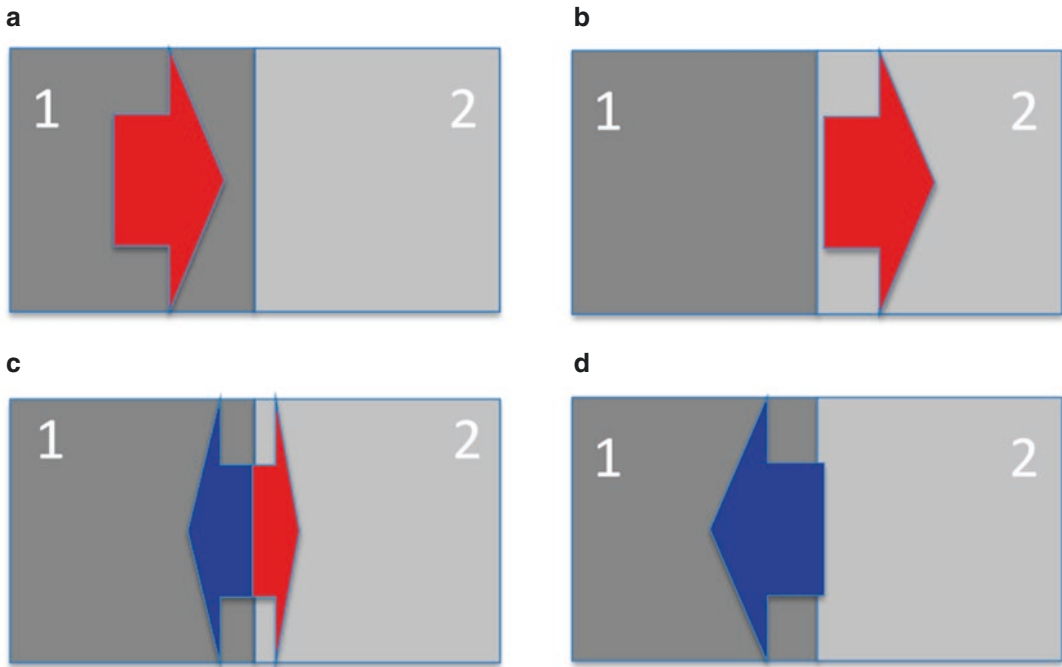


Fig. 2.5 Stress transmission across the interface between two materials. (a) A shock wave moves through material 1 towards an interface with material 2, (b) If the impedance of material 1 and 2 is the same, all the stress transmits, (c)

If there is a difference in impedance, some of the stress transmits and some is reflected, and (d) If the impedance of material 2 is very low compared to material 1, then most of the wave is reflected back into material 1

Here, it is important to remember that **stress, force and velocity are all vectors**; they have a magnitude and a direction. By convention, we make an increase in velocity from left to right to be positive and right to left as negative. A wave which acts to compress a material will be regarded a positive stress, and a wave which puts the material into tension or releases will be regarded as negative change in stress.

In Fig. 2.5a, a stress wave travels through material 1 of impedance Z_1 towards an interface with material 2, impedance Z_2 . Figure 2.5b shows what happens when the wave reaches the interface if the impedances of material 1 and 2 are the same; all the stress wave transmits through the interface. The value of the transmission coefficient is 1 and so the stress in material 2 is exactly the same as the stress level in material 1, i.e. both end up at the same stress. The amount reflected is 0 and so the stress in material 1 remains unchanged.

In Fig. 2.5c, the materials have impedances that are of a similar magnitude but different values; Z_1 being half the value of Z_2 . Calculating the stress transmission and reflection coefficients results in $T = 4/3$ and $R = -1/3$. This means that that stress produced in material 2 is higher than that initial wave. This may seem odd, until it is remembered that impedance is related to density and sound speed, so material 2 in this case is denser and/or stronger than material 1; effectively material 2 slows down the motion of material 1; the result is higher stress and less particle velocity.

While the transmitted force is still going in the positive direction, it is higher by $4/3$ over the initial stress in material 1. The reflected portion has a negative reflection coefficient, and the wave is propagating in a negative direction. Mathematically, two negative numbers multiplied together equal a positive, so what this implies is that the amount of reflection means we have a stress change of $+1/3$ of the initial pressure **adding** to

the initial pressure. The stress in material 1 increases as the denser, stronger material 2 prevents it from moving forward, effectively swapping a change in velocity for higher stress.

This reveals an important point; if surfaces remain in contact, then the stress is the same in both sides of the interface. This is the basis of a technique called impedance matching used in shock physics to determine the stress and velocity of materials under the action of shock waves.

A material with a high density and high sound speed will have a higher impedance and as a result will exert a higher pressure at a given impact velocity than a low density or low speed material. This means that a much higher stress is produced by tungsten, a preferred material for anti-tank weapons, striking an object at a given velocity than the lower impedance iron, while Perspex will produce a much lower velocity.

In the case of Fig. 2.5d, the impedance of material 2 is very low compared to material 1. In this case, the change in the reflected stress is a value of 1 and it is going in the negative direction. Following the argument above, this means it changes the stress by -1 . This implies that the stress change of the reflected wave cancels the stress of the original wave. In this case, the stress falls to zero and the energy of the stress pulse accelerates material 1 to a higher velocity, approximately doubling the particle velocity.

2.5.5 The Solid–Air Interface

After the stress wave from the detonation has been transmitted through the casing, accelerating it

and ultimately shattering it, it is then transmitted through the surrounding soil and sand compressing and fracturing it. When the stress pulse arrives at the solid/air interface from the transmission-reflection coefficient, it is clear that the vast amount of the stress is reflected from the solid/air interface. This reflection is like the case in Fig. 2.5d discussed above; the velocity of the sand/soil particles double as the stress drops to zero. Sand/soil has a very limited tensile strength so the result of this is to throw the sand and soil from the surface as a cloud of fast-moving debris.

While the stress wave compresses the material and ultimately results in a cloud of fast-moving debris, the product gases from the explosive devices are also pushing the soil and fragmenting the compacts formed by the stress wave. It is the expansion of the hot product gases that produces the largest effect of the blast wave.

2.6 Blast Waves

The product gases have a velocity of approximately 2000 ms^{-1} , considerably higher than the sound speed in air of 330 ms^{-1} . The resulting high-pressure pulse of air is pushed outwards by the hot explosive products. In order to allow comparison between charges of different sizes and compositions, explosive engineers conducted experiments using the simplest scenario possible—a bare explosive charge in an empty, flat field. This has resulted in a large body of blast wave literature based around the classic ‘Friedlander’ blast wave form.

Fig. 2.6 The classic Friedlander form of a blast wave

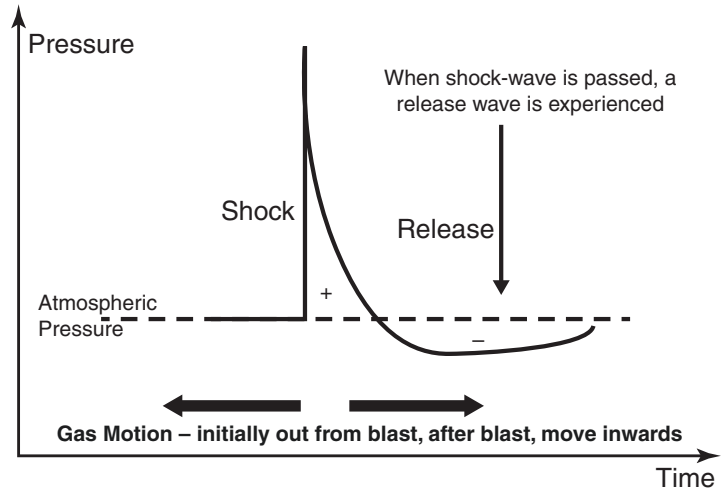


Figure 2.6 shows the pressure-time profile of this classic blast wave. After the initial rapid rise of the blast wave, there is a region of positive pressure, accelerating outwards from the explosion. The speed of the gas moving behind the blast front, in the so-called blast wind, can be as high as 2000 km h^{-1} . This is followed by a release wave that drops the pressure below atmospheric pressure. The release occurs as both air and product gases have expanded outwards, away from the place where the explosion initiated. As a result, the explosive products have expanded and therefore performed ‘work’ on the surroundings and started to cool. This leaves a partial vacuum in the region of initial explosion, and this lower pressure now causes air and gases to flow backwards over a longer period to equalise the pressure. The resulting push-pull movement experienced in the blast wave can be especially damaging to structures and humans.

This simple waveform was often observed in much early research into the effects of blast on humans. These studies used data either from open explosive ranges or with well controlled blast reflections from single walls or barriers. It is important to note that in a cluttered urban or vehicle environment, a casualty will experience a number of waves—those directly arising from

the charge and those reflected from a wide variety of surfaces and arriving from different directions. In general, the amount of reflected pressure waves can be equated to more damage and injury.

2.6.1 Change in Impedance of a Gas in a Blast Wave

In the discussion above, the energy deposited in a material can manifest itself in a number of ways; it can give the material kinetic energy, for instance, and it can compress the material increasing its temperature.

In many engineering applications, solids and liquid are often assumed to be incompressible. In shock wave studies, this is not the case and compressions which halve the volume of the material are relatively common. Gases, however, are very compressible. This means that blast waves are supersonic with respect to low pressure sound waves and they also are associated with a very large change in impedance and often with a large increase in temperature. Figure 2.7 shows the change in impedance of air with pressure. Atmospheric pressure is located at the point where the impedance increases sharply.

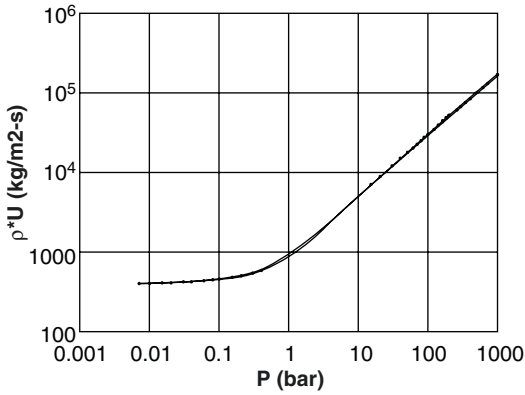


Fig. 2.7 The change in impedance of air with pressure

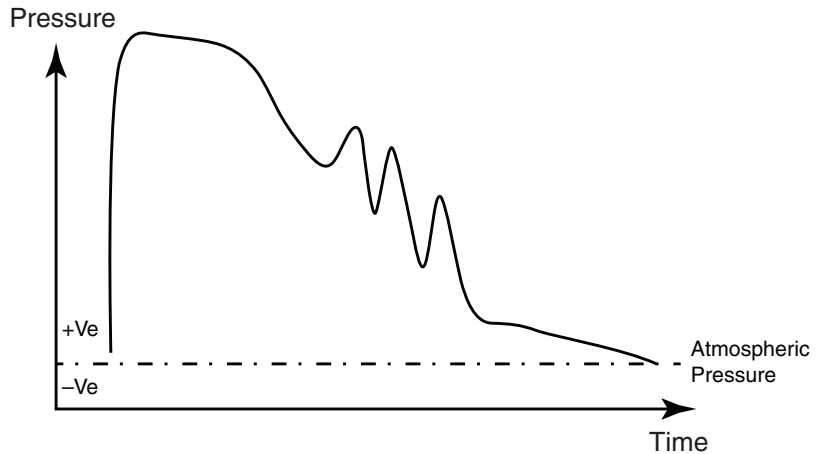
A major difference between shocks in solids and liquids and blasts is that blast waves from munitions tend to have durations measured in **milliseconds**, while shock waves in solids exist on timescales of **microseconds**. This thousand-fold difference in duration is why the relatively modest pressure seen in a blast wave can produce more movement and damage than the much higher pressures in shock waves.

2.6.2 Reflected Waves

While the compression of the air produces a large change in impedance, it is still the case that the impedance of the compressed gas is very much lower than that of any solid or liquid. When the wave hits against a solid barrier, a compressive pulse is transmitted and the stress in the gas also increases. Calculating the values of the reflected stress change indicates that the stress level almost doubles.

In the case of an explosion in an enclosed space, or in the partially confined space below a vehicle, there is time for multiple wave reflections; this leads to complex blast waveforms of widely differing stress histories. Within a vehicle, the reflections add to the injuries seen, over and above the push-pull effect seen in the relatively simple Friedlander waveform. Figure 2.8 shows an example of the type of waveform seen inside a vehicle, showing a longer lower level with additional pressure spikes.

Fig. 2.8 Waveform showing a possible form of loading seen due to reflections internal to a vehicle



2.6.3 Temperature Rise

As well as the motion of the blast wave there is also a temperature rise associated with it. This can result in burns and combustion. Inside a vehicle, the heat deposited into a material can be divided almost evenly between the heat from the intense light flash associated with the detonation or gas compression while physical contact with the hot gas deposits the other half of the energy. The timescale for this energy transfer is of the order of milliseconds.

Shock waves also result in significant heating within metals; even after the metal has been dropped back to normal stresses, there may be a residual temperature increase in the fragments of over 100°C. The timescale for this heating is in the order of microseconds.

the effects of small-scale experiments to be extended to larger explosives charges.

The two terms used in virtually all scaling equations are (1) the explosive mass and (2) the mathematical cube of the distance between the charge and the target, i.e. the increase in volume in which the energy is deposited and ultimately dispersed.

There are often other terms involved; one of the easiest to conceptualise is the distance of the charge above the ground. If the charge is in mid-air, then the energy expands evenly in all directions, effectively spreading the energy through a sphere. If the charge is on the ground, however, then the effects of wave reflection occur. The gas has very low impedance compared to the ground and so virtually all the energy is reflected back into the expanding hemi-sphere above the ground. Within the hemi-sphere, the energy and pressure are approximately doubled compared to that of the mid-air charge.

Another simple comparative scale between explosive types is that of 'TNT equivalence'. Historically, TNT was a widely used material, which could be easily melted and cast into a variety of shapes, unlike many other explosive materials. Given its castable nature, many experiments were conducted, resulting in large databases. TNT equivalence is a simple factor that allows a well-defined reference point for the broad comparison of the effects on a non-TNT explosive charge to be estimated.

2.7 Comparing Explosive Scenarios: Scaled Distance and TNT Equivalence

Munitions and explosive charges come in a range of sizes and vary in terms of materials. In the technical literature, the term 'scaled distance' is often used to relate the effects of large explosive charges over tens of metres to those of small charges at close range. This is useful as it allows

2.8 The Three-Dimensional World and the Physical Basis of Blast and Fragment Injury

The real world has a complex topography and is made of a wide variety of materials, many of which change their properties based on the accelerations produced in them by an explosion. This somewhat mundane statement also indicates the difficulty of understanding the precise effects in terms of the materials and the three-dimensional world. A well-founded method, however, is to take that complex situation and divide it into smaller, more tractable parts.

2.9 Summary/Conclusion

This chapter has given an overview of the basis of explosive technology and presented some of the basic processes relevant to the blast process. The importance of the detonation wave, stress transmission, fragmentation, the ejection of sand/soil, expansion of the product gases and flash heating has been introduced using simple first-order approximations.

The complexity of the mechanical processes and the resistance of the human body can result in injury patterns that show effects that are distant from the immediate blast or impact. It is increasingly possible, however, to adopt an interdisciplinary approach that can bridge the vital mechanical-biological gap in our knowledge.

Following chapters in this book will address and expand on these issues.

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