

CHAPTER 9

EXPLOSIONS IN AIR AND WATER

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9 EXPLOSIONS IN AIR AND WATER

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9.1 AWARENESS SUMMARY

Explosions in air and water are often considered together as one of their primary damage mechanisms is caused by expanding gases, which in air creates the blast effect and in water the bubble pulse effect. As can be seen in Chapter 11, High Explosives, weapons that wish to maximise either blast or bubble pulse damage will generally use the same type of explosive, which maximises the energy in the expanding gases.

9.1.1 Explosions in Air

9.1.1.1 Blast waves

When an explosive detonates in air it generates a shock wave, an intense pressure wave travelling faster than the speed of sound in air (approximately $330 - 340 \text{ m s}^{-1}$ at sea level depending on temperature). A point some distance from the explosion will experience an instantaneous rise in pressure that within milliseconds falls back to ambient pressure and then creates a negative

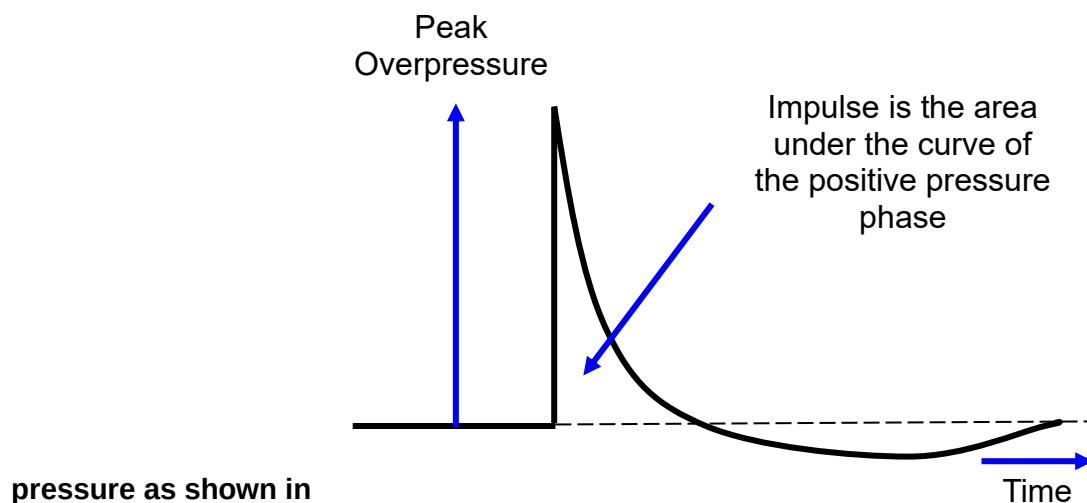


Figure 9-1 where the dotted line is ambient air pressure.

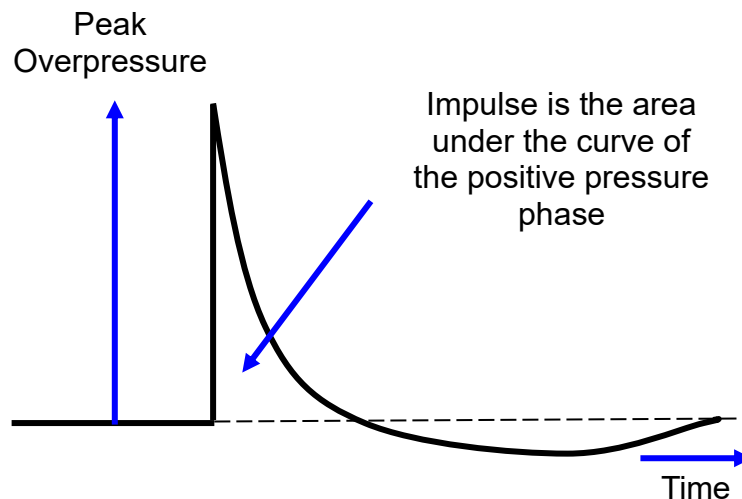


Figure 9-1 Blast overpressure vs. time

The peak pressure of a blast wave is called the peak overpressure, which is the pressure above ambient air pressure and is often used as a measure of damage potential of that blast wave. This is a convenient way to consider damage potential although it is more correctly assessed by knowing the impulse, which depends not only on the peak overpressure but also on the duration of the positive overpressure.

The negative pressure phase for most explosions, unless they are very large such as from nuclear weapons or kiloton explosive accidents, does not have the potential to cause damage but is important to understand the after effects of damage caused by the positive phase. For example when a blast wave impacts a building and breaks windows much of the fragmented glass will be accelerated forwards and enter the building. However, as the negative phase is a suction effect some will be caught and sucked back out of the building and fall to the street below. This has been seen on many occasions when a terrorist vehicle bomb has been detonated in a city.

9.1.1.2 Factors that affect blast damage potential

There are a number of things that can affect the size of blast from an explosion, the most important being:

- Size of the explosive charge
- Type of explosive
- Distance from the explosion

Other factors include:

- Casing on the charge (the greater the weight of casing the less will be the blast)
- Altitude (as altitude increases blast values decrease)

9.1.1.2.1 Size of the explosive charge

Increasing the size of an explosive charge does not increase the blast effectiveness by the same amount. If a charge weight is doubled this will only increase its effectiveness by around 13 %. To double the effectiveness such as having twice the blast pressure at a given distance from an explosion will require 8 times as much explosive and to triple the effectiveness requires 27 times as much.

9.1.1.2.2 Type of explosive

Some types of explosive can produce better gas expansion effects than others and are formulated for this purpose. Details are given in Chapter 11, High Explosives (see 11.3). It is common to take TNT as a standard when considering blast performance and compare others by using a TNT equivalence value. This means that if an explosive type has a TNT equivalence of 1.2 then a given charge weight, say 1 kg, will produce the same blast effect as 1.2 kg of TNT. These values will usually be in the range of 0.8 (e.g. ANFO) to 1.2 (e.g. Torpexes). One kg of ANFO will produce the same blast effects as 0.8 kg of TNT.

9.1.1.2.3 Distance from the explosion

Peak overpressure from an explosion falls off very rapidly with distance as shown in Figure 9-2. Doubling the distance reduces the blast overpressure to one quarter and tripling it to almost one tenth. This demonstrates the effectiveness of barriers that control how close vehicles can approach a building when protecting from terrorist attacks.

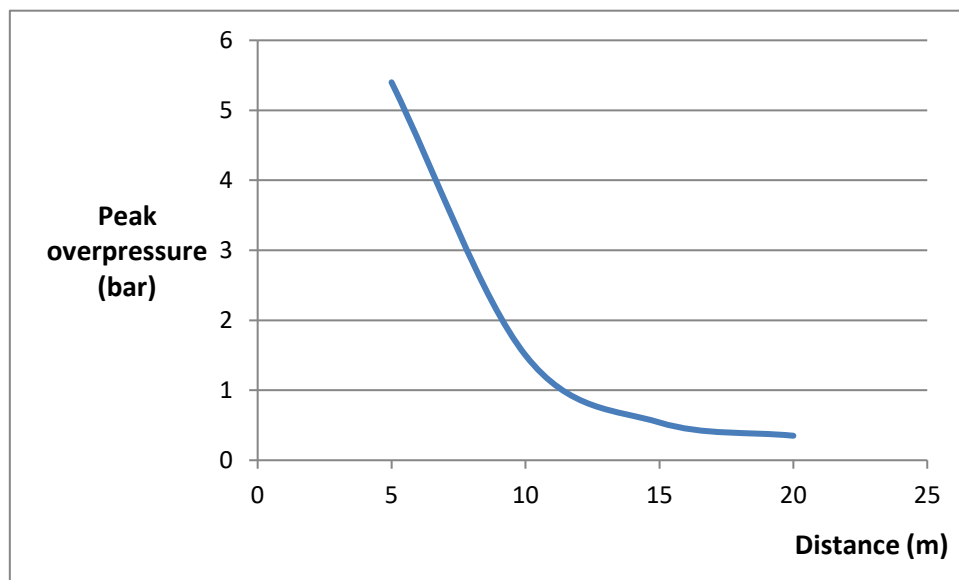


Figure 9-2 Overpressure vs. distance for a 50 kg TNT explosion

9.1.2 Explosions in Water

9.1.2.1 Primary shockwave

When an explosive detonates underwater an intense pressure pulse called the primary shockwave travels away from the explosion at a velocity faster than the speed of sound in water, which is approximately 1500 m s^{-1} . Water is a good medium to transmit shockwaves and pressures measured in hundreds of bar (10s MPa) may be produced within the first 50 metres from a large charge such as a depth charge and still many tens of bar ($>1 \text{ MPa}$) at over 100 metres. In contrast a charge of similar size detonated in air would produce a blast wave with a peak overpressure no more than 0.2 bar (20 kPa).

If this primary shockwave hits a ship it has the potential to damage sensitive equipment and if close to the explosion damage even robust equipment. The shockwave accelerates the structure, which then interacts with anything in contact. This can include the ship's crew and has been known to cause ankle fractures.

9.1.2.2 Bubble pulse

After the primary shockwave has left the explosive charge a high pressure sphere of gas explosion products then begins to expand as a bubble in the water. This expansion continues due to inertia to a point where the pressure inside the bubble becomes lower than the pressure in the surrounding water. The surface of the bubble then begins to move back and the bubble shrinks. Again due to inertia as the bubble collapses it reaches a point where the pressure inside the bubble is greater than the surrounding water and so begins to expand again. At this point it releases a pressure wave in to the water of much lower pressure than the primary shockwave but with a much longer duration. This expansion and contraction can cycle many times each time producing a pressure wave.

For the bubble pulse pressure waves to be damaging the process must occur in close proximity to the target as is often the design intent of underwater weapons. The overall effect of detonating a large explosive charge of a few hundred kilograms under the keel can break the back of the ship.

9.2 GAS EXPANSION EFFECTS FROM EXPLOSIONS

Expanding hot gases produced by an explosion can perform work on the surroundings. This is the mechanism by which explosives can be employed to produce a number of effects:

- Lifting and heaving
- Cratering
- Creation of airblast
- Production of underwater bubble pulses

9.2.1 Work Capacity

In air the energy of the detonation shock wave from an explosion is quickly dissipated as heat and is collected by the gaseous explosion products as they expand. Nearly all the intrinsic energy of the explosive (the Heat of Explosion, Q) is therefore available for work. The maximum available work (A) is expressed by the work integral shown in Equation (9-1).

$$A = - \int_{v_i}^{v_f} p dv = - q \quad (9-1)$$

Where: v_i is the initial volume of the gaseous explosion product; v_f is the final volume of the gaseous explosion product; p is the gas pressure; q is the heat content of the gases in their final state.

Usually v_f is very much greater than v_i so that the mechanical efficiency of an explosion is very high.

In CHNO explosives where all the products of reaction are gaseous, A is generally within 7 % of Q . For explosives which produce condensed or solid materials in the reaction products, thermal equilibrium between the gas and solid phases may not be maintained during the gas expansion stage, the solid phase retaining a significant proportion of its energy. Many explosives generate appreciable quantities of solids or liquids in their reaction products. TNT produces free carbon and black-powder produces potassium salts including oxide, carbonate, sulphide and sulphate. Explosives containing aluminium yield solid aluminium oxide. For TNT, about 20 % of the heat of explosion is contained in the solid explosion products, of which only half becomes available to do useful work.

9.2.2 Force, Power and Strength of Explosives

In practical situations it is rarely possible for the work integral to be evaluated since the value of v_f when no more useful work is being done on the surroundings cannot be determined. The performance of an explosive through gas expansion is therefore expressed in practical units of force, power or strength.

9.2.2.1 Force Constant

The chief performance parameter for a gun propellant is its 'force constant', the maximum amount of work which can be done by a unit mass of propellant. A more practical measure is the pressure produced by unit mass of propellant when contained in a fixed volume, so that

$$\text{Force Constant (F)} = nRT_d \quad (9-2)$$

Where: n is the number of moles of gas per unit mass of explosive; R is the molar gas constant; T_d is the temperature of detonation.

For example, RDX has a value of 0.041 mol g^{-1} for n and 4255 K for T_d . The molar gas constant has a value of $9.31 \text{ J mol}^{-1} \text{ K}^{-1}$ given a Force Constant for RDX of 1434 J g^{-1} .

In general, explosion products of low molar mass favour high values of n . They also tend to have lower heat capacities, resulting in higher temperatures of gaseous products.

9.2.2.2 Power Index

Although Force is a valid parameter for use with high explosives it is more usual to employ a parameter called the 'Power Index'. Power is related to the amount of gas produced and the amount of heat available to expand the gases. When used in connection with explosives the word 'power' does not refer to the general definition of power, that is the rate of doing work, but rather to the total work output. The 'Power Index' is obtained by comparing the value of [Heat of Explosion (see 4.4.2) ($Q \text{ J g}^{-1}$) x Gas Volume (see 4.4.3) ($V \text{ cm}^3 \text{ g}^{-1}$)] for an explosive as a percentage of that of a standard explosive, picric acid though this is no longer used as a practical explosive.

The use of Power Indices to compare explosive for their potential to perform work through gas expansion can be justified as follows. The most accurate way to assess individual explosives is by applying its Force Constant (F) as shown in Equation (9-2). Since one mole of an ideal gas occupies the same volume, 22.4 dm^3 at standard temperature and pressure and n has the units moles g^{-1} then n is directly proportional to V . Temperature of detonation (T_d) is related to Heat of Explosion (Q) as shown in Equation (9-3).

$$T = \frac{Q}{\bar{a}_c} \quad (9-3)$$

$\bar{a}_c$ is the mean molar heat capacity of the gaseous products and this value will depend on the ratio of CO , CO_2 , $\text{H}_2\text{O (g)}$, H_2 and N_2 . Clearly this will differ for every explosive; however, for military explosive formulations they are quite similar. Therefore it is acceptable to say that T_d is proportional to Q and that F is proportional to $Q \times V$.

As an example the Power Index of RDX is given by:

$$\text{Power Index} = \frac{Q_{\text{RDX}} \times V_{\text{RDX}}}{Q_{\text{Picric Acid}} \times V_{\text{Picric Acid}}} \times 100 \quad (9-4)$$

Q values: RDX 5125 J g^{-1} , Picric acid 3745 J g^{-1}

V values: RDX 0.908 dm³ g⁻¹, picric acid 0.780 dm³ g⁻¹

Therefore:

$$\text{Power Index} = \frac{5125 \times 0.908}{3745 \times 0.780} \times 100 = 159$$

9.2.2.3 Strength

Commercial explosives manufacturers express the performance of their products in terms of strength. This is measured by comparing the work done by an explosive with that done by either an equal weight (weight strength) or an equal volume (bulk strength) of a standard explosive. The standard chosen is often blasting gelatine; however, other commercial explosive standards are sometimes used. Care must be taken when considering a strength value for a particular product as the standards can be quite different in strength.

9.2.3 Measurement of Power and Strength

Many methods have been developed for the measurement of the maximum power output of explosives. A typical method consists of detonating the explosive in a water-filled quarry and estimating the total energy liberated by measuring the pressure in the shock waves produced, the gas bubble size and frequency of oscillation. The practical value of these methods is limited by the inconvenience of the experiment and the fact that the efficiency of explosives in real situations is rarely ideal. Methods which may be used in a laboratory are more useful.

9.2.3.1 Trauzl lead block test

This classical method of measuring 'power index' was established at the International Congress of Applied Chemistry in 1903. The test provides a ready means of measuring the relative power of an explosive though the result provides an index of brisance as well. A cylindrical block is cast from pure lead, its dimensions being 200 mm for both length and diameter. The cylinder has an axial hole 25 mm in diameter and 125 mm in length. Ten grams of explosive wrapped in tin foil and fitted with an electric detonator are inserted to the bottom of the hole and tamped with graded dry sand until the hole is full. The charge is fired and the hole enlarged to a pear shape by the explosion as shown in Figure 9-3. The new volume of the hole is measured by filling it with water and the increase in volume obtained by subtracting the original volume (61.5 cm³). A parallel test with the standard explosive picric acid is also carried out and the 'Power Index' obtained by comparing the relative crater volumes.

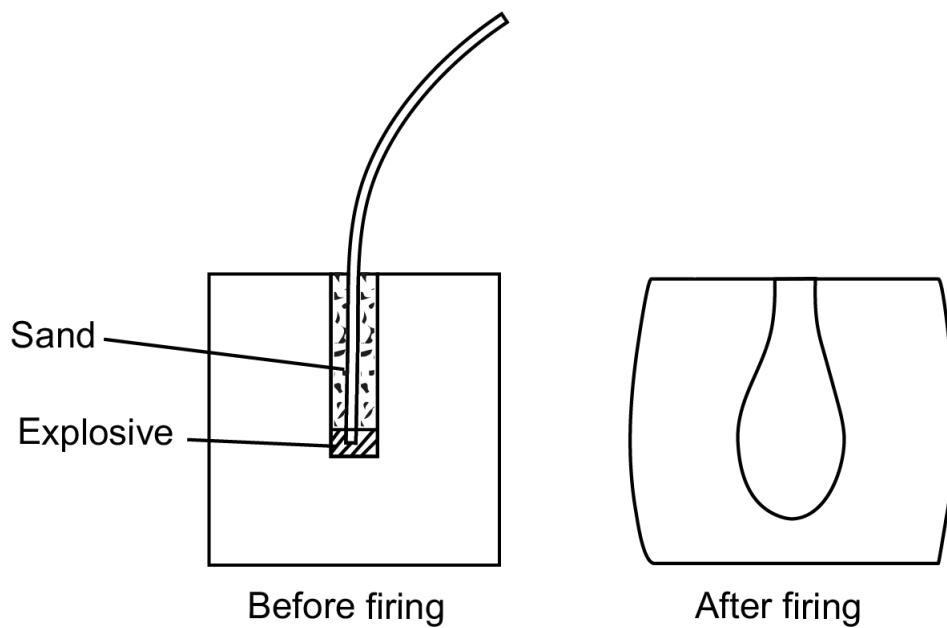


Figure 9-3 Lead block test

Criticisms of the test include the fact that the results depend on the starting temperature of the lead block, the number of times the lead has been recast and the nature of the tamping material. Though the test is no longer employed, accepted results exist for most explosives and are still commonly used (Table 9-1). It is still of value in studying weak explosives which are unsuitable for measurement in the ballistic mortar.

Table 9-1 Calculated and Experimental Power Index Values

Explosive	Calculated	Trautzl lead block	Ballistic mortar
Nitroglycerine	171	175	200
PETN	161	165	179
HMX	160	160	-
RDX	159	170	194
Torpex-2 (RDX/TNT/A1)	158	155	-
Amatol 80/20 (% w/w)	126	135	128
RDX/TNT 60/40 (% w/w)	138	125	-
Tetryl	123	120	132
Pentolite 50/50 (% w/w)	129	115	-
TNT	117	95	86
Lead styphnate	21	39	-
Lead azide	13	37	-

9.2.3.2 Ballistic mortar

Various mortars have been designed but an internationally accepted standard has been agreed by the International Committee on the Standardisation of Tests on Explosives, Sterrebeck, Belgium (1962) and the European Commission for the Standardisation of Explosives Testing, and rests on a design by the American company, DuPont. The principle of the mortar is illustrated in Figure 9-4. A 3 m long pendulum is fitted with a bob weighing 333 kg. A hole in the bob is fitted with a shot 12.37 cm in diameter, weighing 16.6 kg and having a clearance of 0.08 mm. Ten grams of explosive are wrapped in tin foil and fired using a plain detonator. The explosive ejects the shot which is captured on rubber matting or by a mound of sand. The recoil of the bob is measured on a scale and is a measure of the work done by the explosive on the system. The mechanical efficiency of the system is low but the results are reproducible and suitable for comparative work.

9.2.3.3 Other tests

The ballistic mortar and Trautzl tests use only 10 g of explosive. Some explosives are too insensitive or have critical detonation diameters which are too large to enable them to be tested by either of these methods. For these explosives, several kilograms may be exploded under water and the oscillation frequency of the gas bubble produced measured and used to calculate the power of the explosive. In a similar vein, another effect from explosive power is

air blast, which also can be used for comparisons. In this case the standard used is TNT and has led to explosives being assessed for blast potential being given a TNT equivalence and described in section 9.3.2.1.

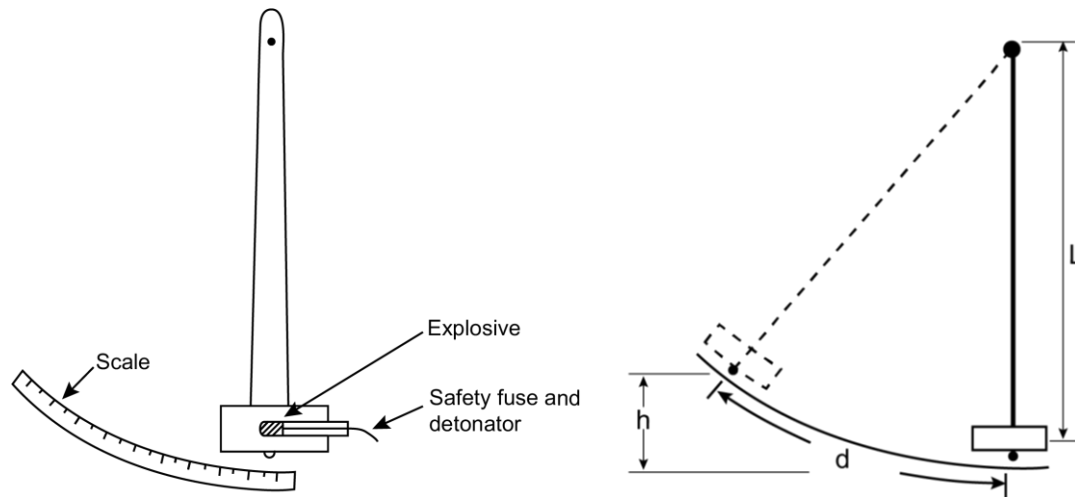


Figure 9-4 Ballistic Mortar

9.3 EXPLOSIONS IN AIR

9.3.1 Formation of Blast Waves

9.3.1.1 Primary shock wave

When an explosive charge is detonated in air the detonation shock wave passes through the charge at several thousand metres per second. When the detonation wave reaches the surface of the charge it is transmitted into the surrounding air. Once transmitted into the air, the detonation wave becomes known as the primary shockwave. No longer sustained by the chemical reactions within the explosive, the energy of the primary shockwave is rapidly dissipated through heating of the air and expansion over an ever increasing volume.

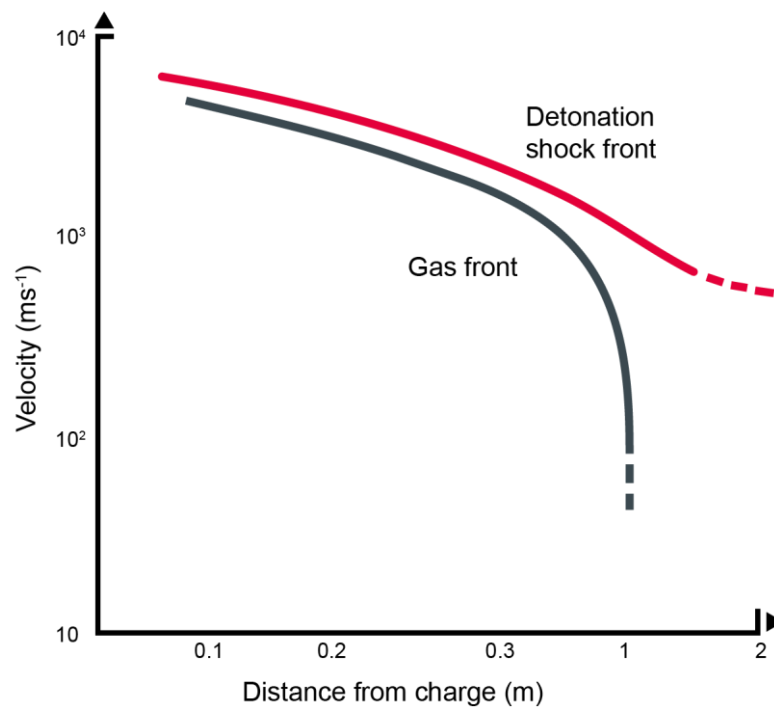


Figure 9-5 Detonation shock and gas front velocities from a 1 kg spherical charge of TNT in free air

9.3.1.2 Formation of the blast wave from expanding explosive gases.

Behind the primary shock wave is an area of high pressure and high temperature gas formed from the gaseous products of the explosion. The gas expands outwards and overtakes the primary shock wave in about 2 to 3 charge diameters picking up the energy deposited by the primary shock. As the gas expands further, the air surrounding the explosive gas is pushed away from the explosion and compressed forming a pressure wave, initially with a pressure profile shown at (a) in **Error! Reference source not found.**. Note that in Figure 9-5 the gas front from a 1 kg detonation has essentially stopped one metre from the explosive charge.

The speed of sound in air depends on its pressure, the greater the pressure the greater the speed of sound. Taking a wave of gas moving outwards, as in **Error! Reference source not found.**, the gas at point 'b' on the pressure curve is moving in air at a higher pressure than the gas at point 'a' and hence moves faster. So over time the gas at point b catches up with the gas at point a, as shown at (b) eventually forming a shock wave at (c). The actual shape of the initial wave has less effect on the eventual shape of the shock wave than the amount of energy released. This difference results in the formation a shock wave through this process called 'shocking up' and has an initial velocity of around 1000 m s⁻¹.

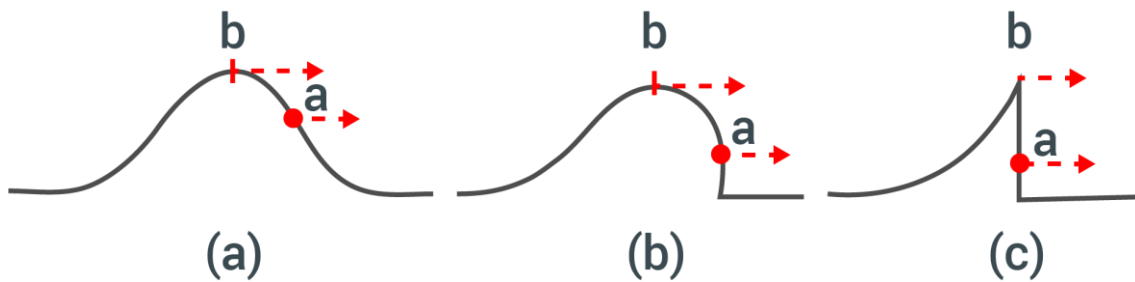


Figure 9-6 Formation of a blast wave

9.3.1.3 Ideal blast wave

For an idealised explosion a pressure transducer at some distance from the charge would record a signal similar to that shown in Figure 9-7. It takes time for the shock wave to reach the pressure transducer and so for some time after the explosion the transducer records the atmospheric pressure, P_0 . The blast wave arrives at time t_a . At this time there is an almost instantaneous rise in pressure to the maximum pressure, known as the peak pressure, P' . The maximum overpressure, P_s , is the maximum pressure above atmospheric pressure and is given by $P_s = (P' - P_0)$.

As the pressure wave passes over the transducer the pressure decays with time. Eventually the pressure drops to atmospheric pressure at time t_d . However, due to inertia of the air molecules that are moving in the direction of the blast wave the pressure drops below the ambient atmospheric pressure producing a negative pressure phase before returning to atmospheric pressure at time t_f . The time $(t_d - t_a)$ is the 'positive duration' of the blast wave and spans the 'positive phase' of the blast wave, that is when the pressure is above atmospheric pressure. The 'negative phase' of the shock wave is when the pressure is below atmospheric pressure and is from time t_d to t_f .

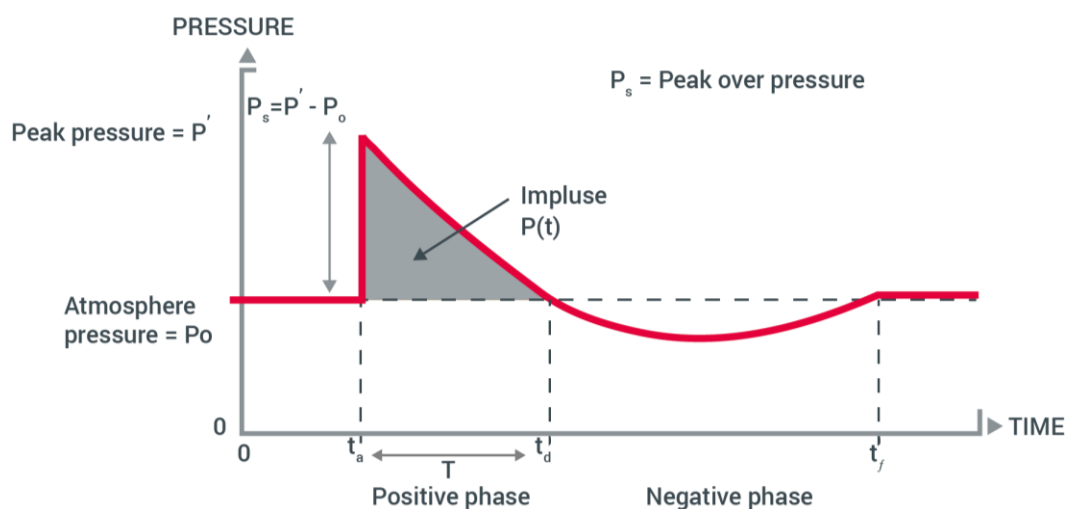


Figure 9-7 Ideal blast wave

The positive impulse, I , of a shock wave is a measure of the pressure multiplied by the duration of the pressure. It is defined as the integral of pressure over the duration of the positive phase of the blast wave as shown in Equation (9-5) where $p(t)$ is the pressure of the shock wave at time t . The impulse corresponds to the shaded area under the positive phase of the blast wave curve in **Error! Reference source not found.** Compared to peak overpressure the impulse gives a more accurate method of assessment of the damage capacity of a blast.

$$I = \int_{t_a}^{t_d} (p(t) - p_o) dt \quad (9-5)$$

As the blast wave travels away from the explosion, its energy is dissipated due to heat losses to the air medium in which it is travelling. As a result the energy density of the wave falls as the wave expands out to cover an ever larger volume. The blast overpressure is related to the energy density and hence it also decreases with distance as shown in **Error! Reference source not found.**

The front of the blast wave has a higher pressure and hence faster velocity than the later part of the blast wave. Hence the front of the shock wave travels faster. As a result the positive duration increases with distance.

Finally the velocity of the shock wave falls to the sonic velocity in air (approximately 330 m s^{-1} at standard temperature and pressure). The wave front becomes less steep and the 'negative phase' (rarefaction) becomes approximately equal to the 'positive phase' in amplitude. The blast wave then resembles an ordinary impulsive sound wave.

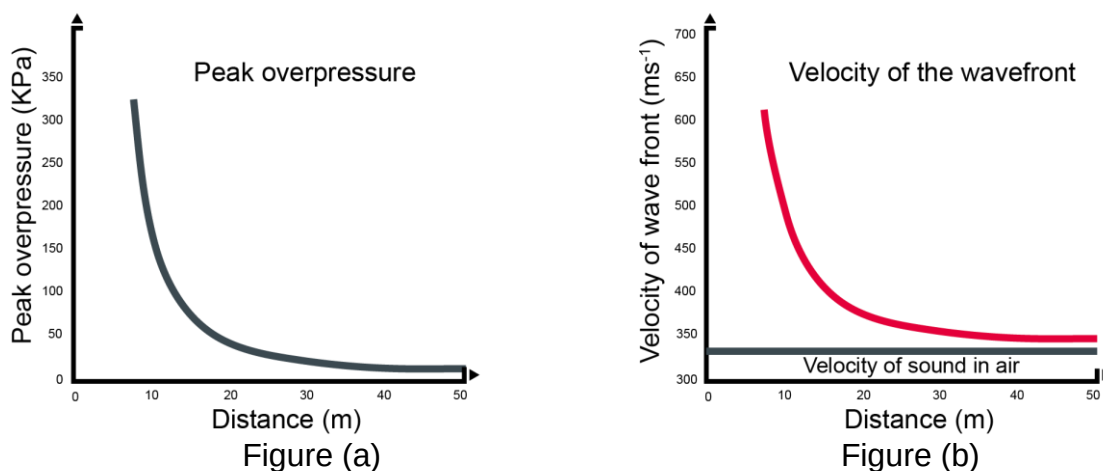


Figure 9-8 Peak overpressure (Figure a) and velocity of the wavefront (Figure b) for 100 kg TNT

9.3.1.4 Shape of the blast wave

The decay of the pressure-time curve at a given location in space can be fitted by the Friedlander equation shown in Equation (9-6).

$$P(t) = P_s \left[1 - \frac{t}{T} \right] \exp \left\{ - \frac{bt}{T} \right\} \quad (9-6)$$

$P(t)$ is the pressure at time t , P_s is the peak overpressure, t is time, T is the positive wave duration and b is called the waveform parameter and is a function of the peak overpressure. The waveform parameter is an adjustable factor selected to fit the curve to provide a method of obtaining the correct blast impulse.

The shape of the pressure/time curve also can be reasonably well fitted by the simpler equation due to Ethridge:

$$P(t) = P_o + P'e^{-ct} \quad (9-7)$$

Where c is a constant obtained from fitting the equation to the data. The equation is an oversimplification but will accurately fit many gauge records over much of the 'positive duration'.

Curve fitting using the Friedlander equation can be particularly useful when analysing blast records. Figure 9-9 shows the pressure vs. time recording from the detonation of a small explosive charge. To obtain accurate values for peak overpressure is not straightforward as the blast gauge takes time to react as the shockwave arrives. To calculate the impulse requires an accurate figure for the positive phase duration, which is usually masked by the pressure spikes overlaid on the true pressure measurement by gauge 'ringing'. This is caused by the natural frequency of some part of the gauge mounting as it is struck by the blast wave. The early part of the decay after peak overpressure and before the first spike from gauge ringing gives accurate data points from which to apply the Friedlander equation.

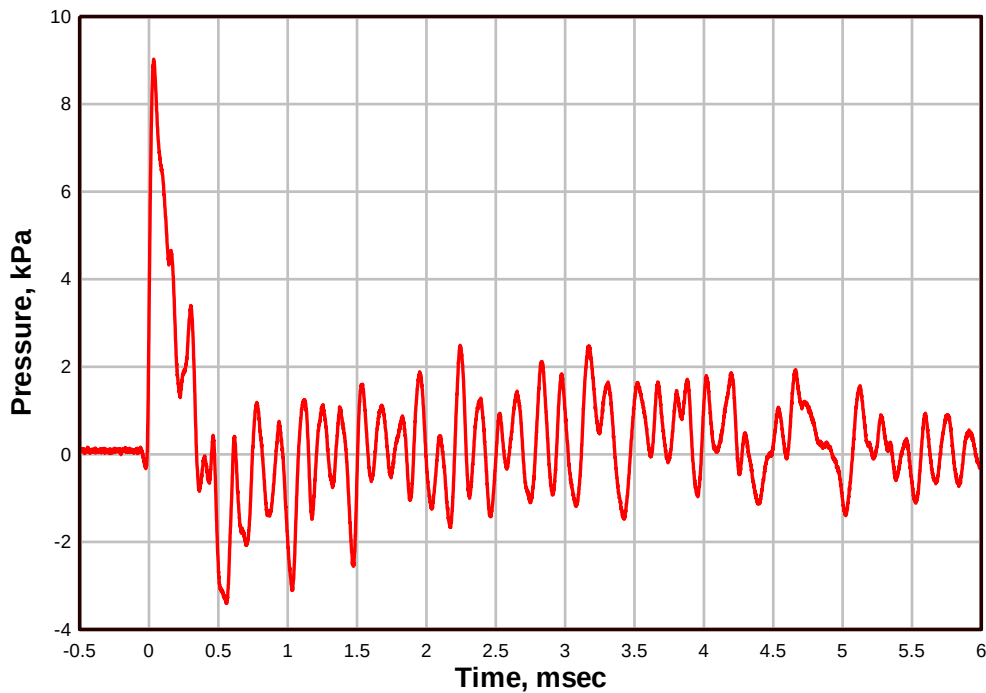


Figure 9-9 Actual pressure vs. time recording from an explosion

9.3.1.5 Velocity of the blast wave

For a simplified blast wave in an ideal gas the blast wave velocity, U_s , and the peak overpressure are related by Equation (9-8).

$$P_s - P_o = \frac{2\gamma \left(\left(\frac{U_s}{a_o} \right)^2 - 1 \right)}{\gamma + 1} P_o = \frac{7 \left(\left(\frac{U_s}{a_o} \right)^2 - 1 \right)}{6} P_o \quad (9-8)$$

For an ideal gas (pressures up to 500 kPa = 5 bar) it has been assumed that the ratio of specific heats = 1.4 and a_o is the speed of sound in air at standard atmospheric temperature and pressure. Rearranging gives a shock velocity as in Equation (9-9).

$$U_s = \sqrt{\frac{6P_s + 7P_o}{7P_o}} a_o \quad (9-9)$$

In practice for shockwaves from explosions the irreversible heating of the air behind the blast wave at high overpressures makes the equations more complex.

9.3.1.6 Non-ideal blast waves

The shock wave in Figure 9-7 is for an ideal blast wave. Quite often the observed characteristics differ from the ideal profile. If the blast source is of low specific energy then the pressure pulse may travel some distance before 'shocking up'. If the blast source is a cased charge then the time/pressure profile may be quite 'spiky' in appearance. This is due to small pressure disturbances superimposed on the primary blast wave. These disturbances are ballistic shocks from casing fragments moving at supersonic velocities. Since the fragment velocities decay less rapidly than the blast wave velocity it is possible for the disturbances to be recorded before the blast wave arrives.

Non-spherical explosive charges, such as cylindrical and rectangular charges, will initially form non-ideal shock waves, often with multiple shocks, as discussed in Section 9.3.1.7. However over time and distance the energy distribution equalises around the shock waves and a single spherical shock wave is formed.

9.3.1.7 Non-spherical charges

Much of the theory for blast waves assumes an ideal blast wave from a spherical charge. In practice most military charges are either based on a cylinder due to the aerodynamic design of projectiles or occasionally cuboids such as plastic explosive.

Each face on an explosive charge will produce a shock wave. Figure 9-10 Shock waves from a cylindrical charge shows the shock waves from a cylindrical charge. The strength of the shock wave depends on the presented area of the face from which the shock wave originates, the larger the presented area the larger the shock wave. Close into the charge this shock wave can be over double that from a spherical charge of the same mass.

As the shock waves expand out they collide. The angle of collision is such that Mach reflection occurs between the colliding shockwaves. This results in Mach stems (known as bridging waves in this instance) and the formation of reflected shock waves also known as secondary shock waves. The secondary shock waves expand out from the line of collision. For cylindrical charges a single secondary wave is observed. For cuboids, several secondary shock waves can be observed. As the shock waves expand, energy is transferred between the shockwaves and eventually a spherical shock wave is formed. Further information on shocks from non-spherical sources can be found in the literature⁽¹⁻³⁾.

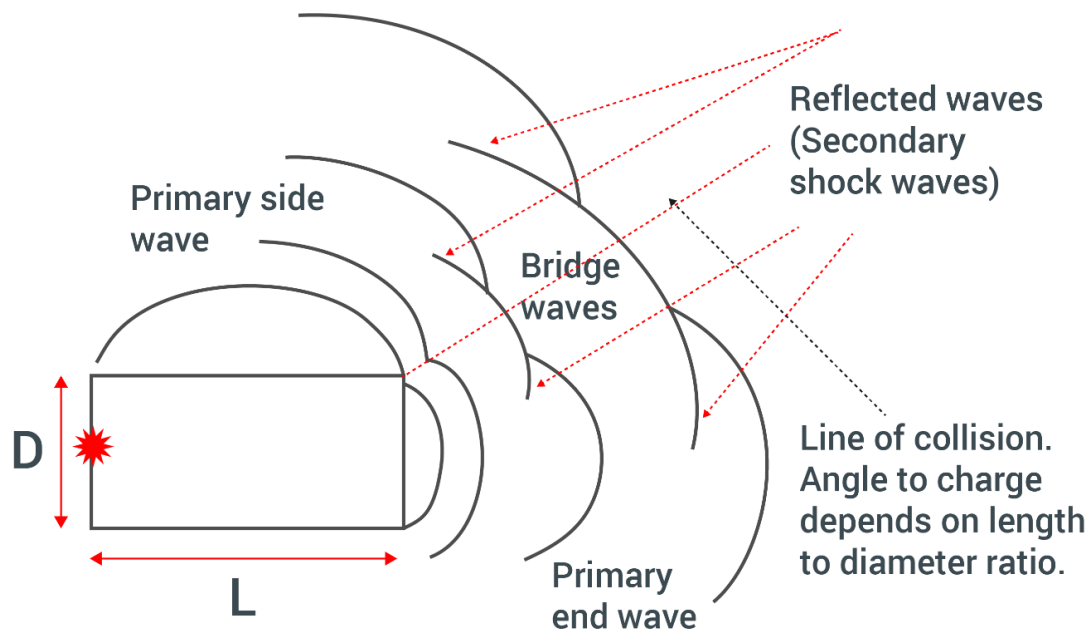


Figure 9-10 Shock waves from a cylindrical charge

9.3.2 Factors Affecting the Size and Shape of Blast Waves

A number of factors affect the magnitude of the blast overpressure; these include the power of the explosive used, the mass of explosive and the distance from the explosion.

9.3.2.1 Comparison of explosives and TNT equivalency

To compare the blast waves from different explosives TNT equivalency is used. This compares the properties, e.g. impulse, peak overpressure, and heat of explosion or power of a blast wave from a given explosive to that of TNT. For each property, TNT equivalence gives a constant that is the ratio of the property of a given explosive compares to that of TNT. For example, the TNT equivalence of Composition B for pressure is obtained from equation (9-10).

$$\text{TNT equivalence}_{\text{pressure}}(\text{Composition B}) = \frac{\text{Overpressure Composition B}}{\text{Overpressure TNT}} \quad (9-10)$$

This is for the same mass and shape of explosive at the same distance from the explosion. For power the TNT equivalence of Composition B is obtained from equation (9-11).

$$\text{TNT equivalence}_{\text{power}}(\text{Composition B}) = \frac{\text{Power Composition B}}{\text{Power TNT}} \quad (9-11)$$

Again this is for the same mass and shape of explosive at the same distance from the explosion.

It would not be unreasonable to consider that the TNT equivalence for a given explosive should be the same no matter how it is determined. However, the TNT equivalence of an explosive can be different for peak overpressure or impulse as shown in Table 9-2. Note that for a given explosive the values of TNT equivalence in the literature can vary depending on the way the data was obtained with values for RDX varying from 1.14⁽⁴⁾ to 1.4⁽⁵⁾. More details on the issues of TNT equivalence can be found in the literature^(6,7).

Table 9-2 TNT Equivalence for Peak Overpressure and Impulse for Some Explosives⁽⁸⁾

Explosive	TNT equivalence pressure	TNT equivalence impulse
ANFO	0.82	0.82
HMX/TNT (70/30)	1.06	1.06
RDX/ TNT (70/30)	1.14	1.09
Composition C4	1.37	1.19
Tritonal 80/20	1.07	0.96
TNT	1.00	1.00

9.3.2.2 Effect of distance

The blast wave from an explosion decreases rapidly with distance, d , as shown in Figure 9-2. How blast overpressure and other parameters such as impulse and blast wave arrival times are affected by the distance from an explosion can be demonstrated by applying polynomials derived from blast measurements^(9,10).

There is some complexity as to the relationship between peak overpressure and distance where, depending on many factors, overpressure may vary proportionally with $1/\text{distance}$ or with $1/\text{distance}^2$ ⁽¹¹⁾. However, the most likely scenario where such a relationship has practical value is for surface burst explosions such as accidental detonation of stored ammunition or terrorist attacks using large vehicle borne devices. Data has been produced for a 50 kg TNT hemispherical burst allowing peak overpressure to be plotted against $1/\text{distance}$ and $1/\text{distance}^2$. Figure 9-11 shows that peak overpressure for distances from 5 to 100 m does not have a linear relationship with $1/\text{distance}$ but when peak overpressure is plotted against $1/\text{distance}^2$ there is a good linear relationship ($R^2 = 0.9959$) as shown in Figure 9-12. The linear fit is even better for ranges close to the charge, 5 to 10 m, with a regression value of 0.999 (Figure 9-13).

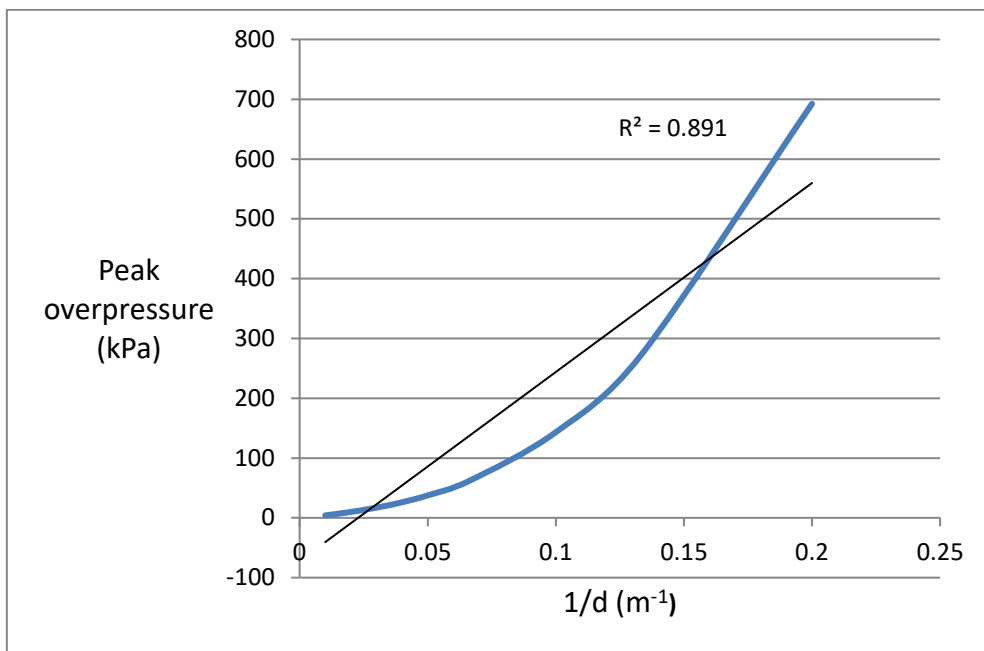


Figure 9-11 Peak overpressure vs. $1/\text{distance}$ for a 50 kg hemispherical TNT explosion from 5 to 100 m

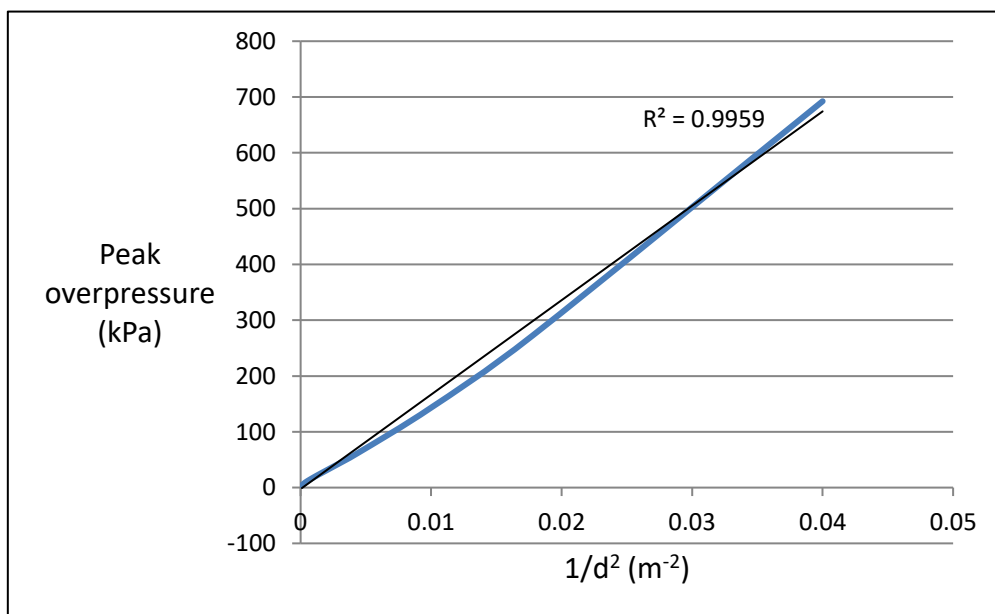


Figure 9-12 Peak overpressure vs. $1/\text{distance}^2$ for a 50 kg hemispherical TNT explosion from 5 to 100 m

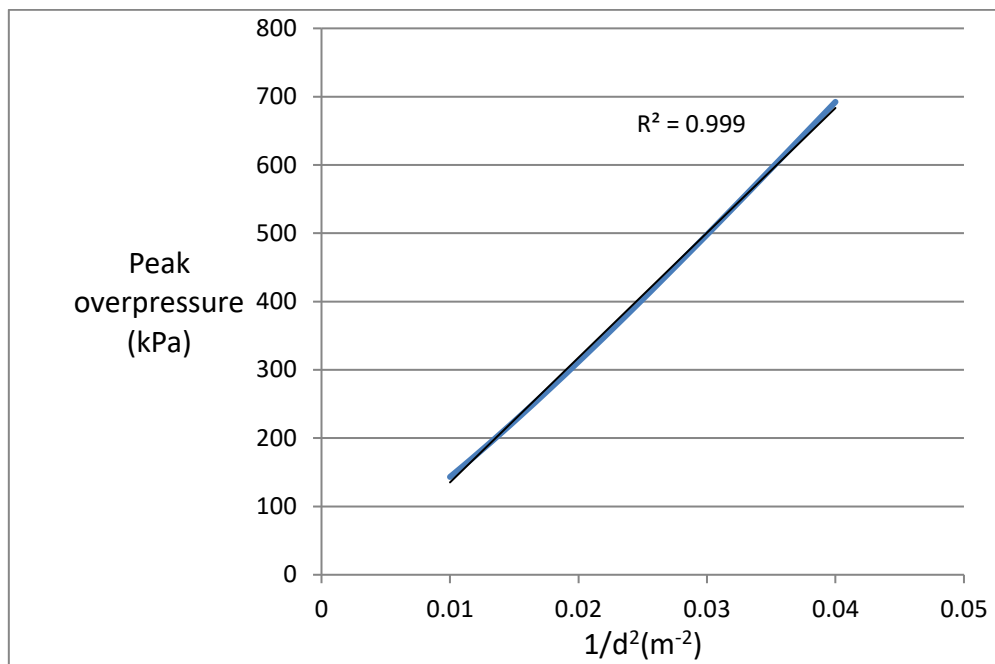


Figure 9-13 Peak overpressure vs. $1/\text{distance}^2$ for a 50 kg hemispherical TNT explosion from 5 to 10 m

9.3.2.3 Hopkinson-Cranz scaling laws

Both Hopkinson⁽¹²⁾ and Cranz⁽¹³⁾ independently found that blast from explosive charges could be scaled by dimension. This is true provided that the charges have the same geometry, are detonated in the same atmospheric conditions and have the same charge to surface geometries. The relationship is known as cube-root scaling or Hopkinson-Cranz scaling as can be demonstrated using Figure 9-14.

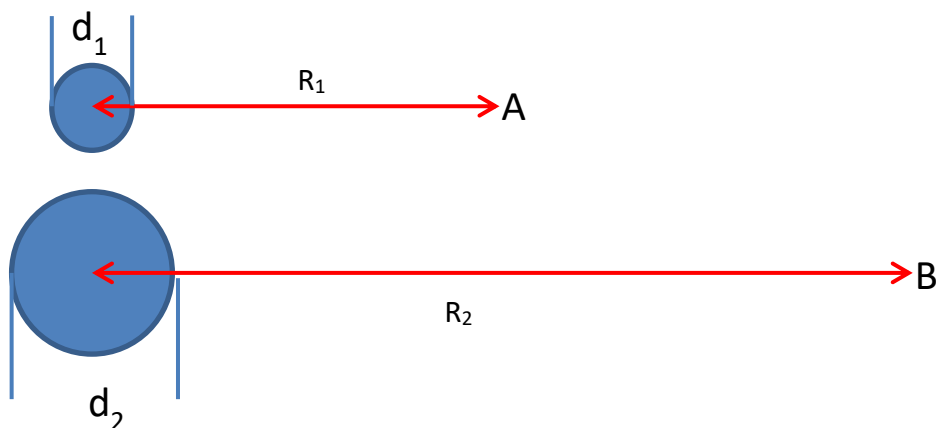


Figure 9-14 Example of Hopkinson-Cranz scaling

In Figure 9-14 d_2 is $2 \times d_1$ and if R_2 is $2 \times R_1$ then the blast wave parameters recorded at points A and B are identical. The volume of a spherical charge is proportional to d^3 and so as d_2 is $2 \times d_1$ then the larger charge will be eight times the volume and if the explosive is the same in both then eight times the mass. From this scaled distance is a value at which the blast wave parameters will be the same for a range of charge weights and distances from the explosion as long as the scaled distance is the same. Scaled distance (Z) is calculated using equation (9-12) where R (m) is distance from the charge and $M^{1/3}$ is the cube root of explosive mass (kg).

$$Z = \frac{R}{M^{1/3}} \quad (9-12)$$

Each value of Z will correspond to a particular peak overpressure and this is further demonstrated with data plotted for peak overpressure vs. distance using three charge weights as shown in Figure 9-15.

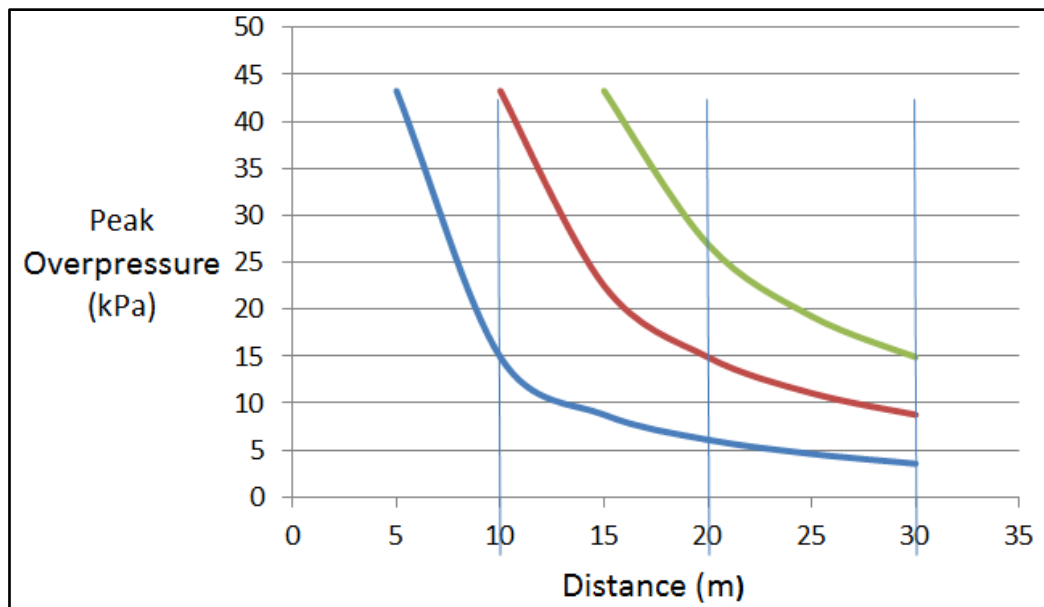


Figure 9-15 peak overpressure vs. distance for 1 kg (blue), 8 kg (red) and 27 kg (green)

It can be seen that all three charge weights give the same peak overpressure of 15 kPa at 10 m, 20 m and 30 m respectively. If peak overpressure is now plotted against $R/M^{1/3}$ then a single curve is produced. The 15 kPa point on each of the curves will become $10/1^{1/3}$, $20/8^{1/3}$ and $30/27^{1/3}$ all giving a scaled distance of 10. If this is carried out across all the data points in Figure 9-15 then the curve shown in Figure 9-16 is produced. To make this easier to use the data is presented with log/log scaling as shown in Figure 9-17.

Scaled distance for given peak overpressures is invaluable for calculating safety distances. For example, the horizontal line drawn on Figure 9-17 is at a peak overpressure of 5 kPa, the maximum peak overpressure that can be accepted to impinge on a building inhabited by the public for explosive licencing

purposes. From the curve the scaled distance is 22.2 and so the storage of explosives with mass explosion hazard can be regulated depending on distance to inhabited buildings and the quantity of explosives stored. By applying equation (9-12) the minimum distance allowed between a storehouse containing 1000 kg and housing occupied by the public is $22.2 \times 1000^{1/3} = 222$ m.

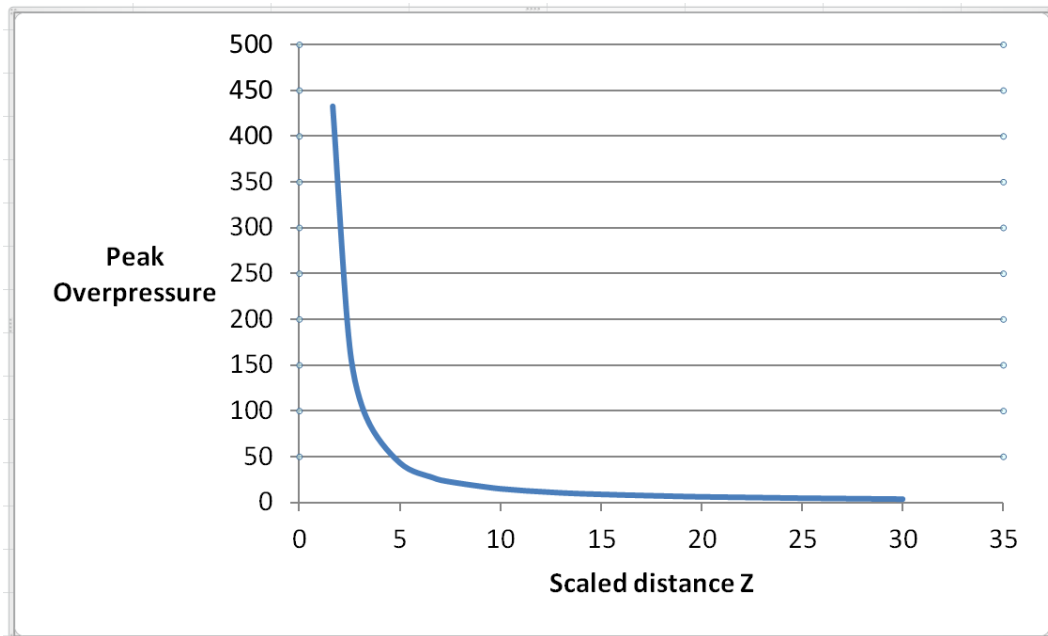


Figure 9-16 Peak overpressure vs. scaled distance from data in Figure 9-15

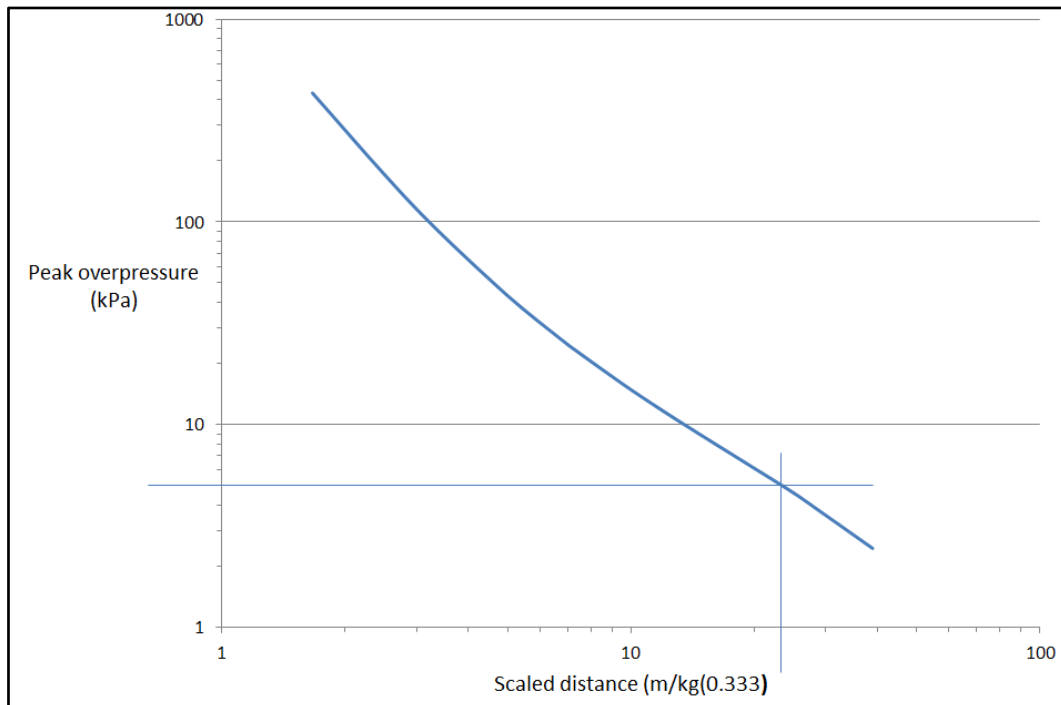


Figure 9-17 Log/log plot of peak overpressure vs. scaled distance

9.3.3 Equivalent Net Explosive Quantity (ENEQ)

The discussion so far assumes a bare charge of explosive. In practice most explosives are contained in some way. The explosives may be wrapped in wax paper, placed in a plastic box or stored in a brick building. Further, some types of ammunition have metal casing designed to fragment. When an explosive detonates, some of the energy goes into breaking up the casing and containment. As a result there is less energy in the blast wave, reducing the strength of the wave. Figure 9-18 shows the effect of casing on the blast waves from an explosion where C/M is mass of explosive charge (C) divided by total mass of explosive plus metal casing (M).

The Equivalent Net Explosive Quantity is defined as the amount of explosive that if the explosive was a bare charge, would give the shock wave observed. That is the amount of bare explosive required to give the shock wave observed after energy has been extracted breaking up the containment. Equivalent Net Explosive Quantity is also sometimes called the Effective Net Explosive Quantity.

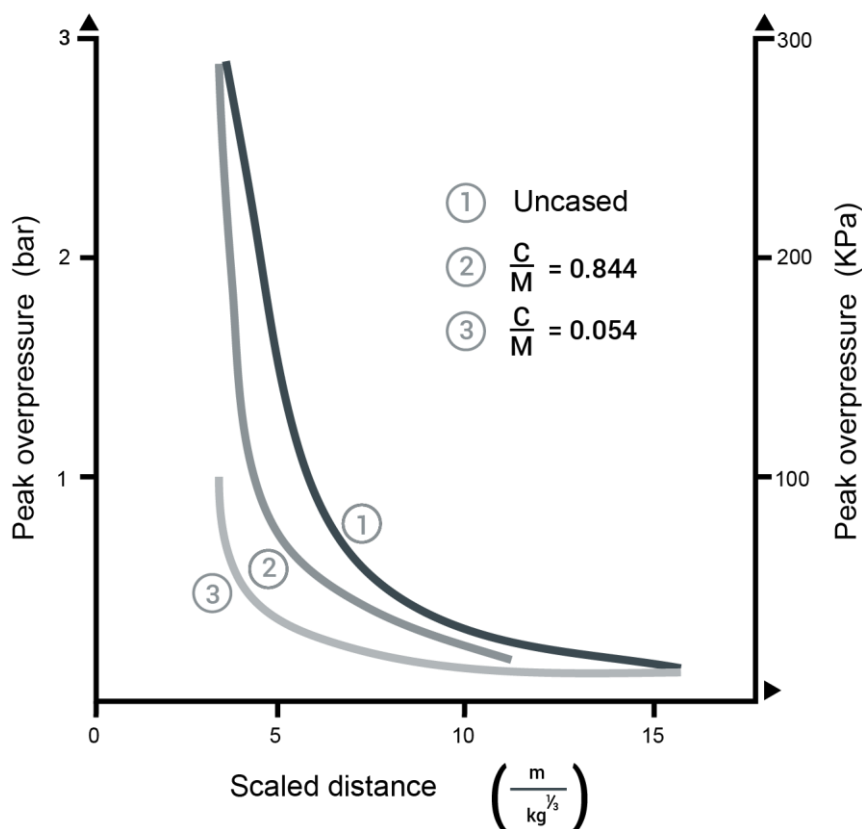


Figure 9-18 Effect of ratio of charge weight/total weight on peak overpressure for similar charge weights of HE in metal cases of different weights

9.3.3.1 TNT equivalency and ENEQ

Section 9.3.2.1 describes how explosives can be compared with TNT in regard to their ability to create blast. This also allows the application of ENEQ when

considering, for example, blast damage potential from stored explosives. If ANFO has a TNT equivalence of 0.82 then 1000 kg of ANFO would produce blast pressures equivalent to 820 kg of TNT. Safety distances, or more correctly safety peak overpressures, are related to a scaled distance as shown in section 9.3.2.3, where a scaled distance of 22.2 gives a peak overpressure of 5 kPa. This assumes the explosive mass used to calculate scaled distance is that of TNT. Therefore, it is not unreasonable to assess the blast damage potential by first converting the mass of explosive in question to that of TNT as shown above.

9.3.4 Reflection of Blast Waves

The above discussion of shock waves in air has assumed an explosion in free air, well away from any reflecting surfaces. It is more usual to be concerned with explosions at or near the ground, or near structures.

9.3.4.1 Explosion on the ground

When a charge explodes on the ground, the blast wave is not able to spread unobstructed in all directions. The blast wave is reflected from the ground into the air. A single hemispherical shockwave is formed. The proportion of the energy reflected depends on the nature of the ground but the increase in overpressure when compared with a free air explosion does not usually exceed a factor of two. Frequently an enhancement of 1.8 is used, allowing for the absorption of some energy into the ground⁽¹⁴⁾. The wave, once stabilised is similar in other respects to one in free air but expanding hemispherically.

9.3.4.2 Normal reflection

When a planar shock wave hits a surface at an angle of 0° as shown in Figure 9-19 the shock wave will reflect from the surface. When the shock wave reaches the surface, the air molecules in the shock wave come to a stop at the surface. The pressure, density and temperature increase above those of the incident shockwave. The gas molecules are then reflected from the surface.

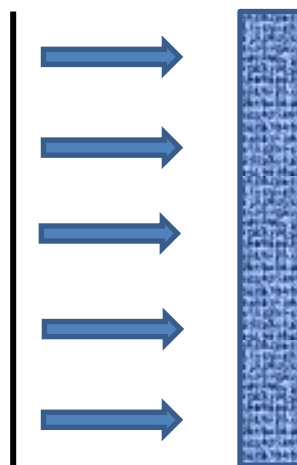


Figure 9-19 A blast wave that will undergo normal reflection

For a weak wave, the overpressure may be doubled by reflection normal to the surface. For a strong wave with a high temperature and pressure, the overpressure may increase up to 20 times or more^(15,16), as shown in Figure 9-20. Damage criteria for hard targets are often quoted in terms of the reflected overpressure rather than incident pressure since it is the instantly reflected pressure which acts on the reflecting target.

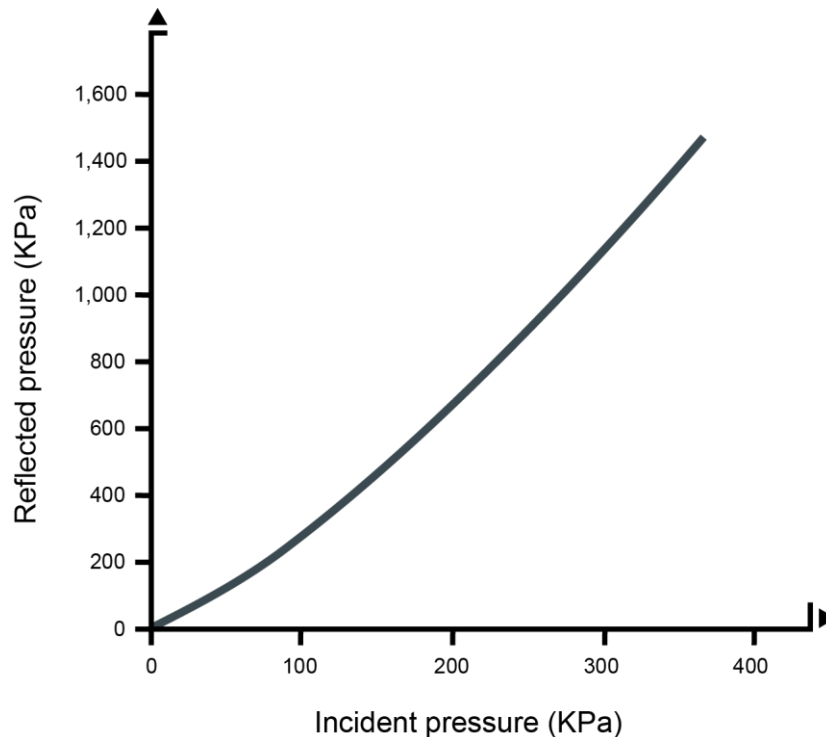


Figure 9-20 Peak reflected overpressure versus peak incident overpressure, for a theoretical target of infinite frontal area

9.3.4.3 Regular reflection

When a shock wave hits a surface at an angle between 0° and 39° regular reflection occurs where the angle of reflection, α_R , is less than the incident angle, α_I , as shown in Figure 9-21. As with normal reflection, the overpressure may be enhanced by regular reflection. The enhancement depends on the angle of incidence, see Table 9-3.

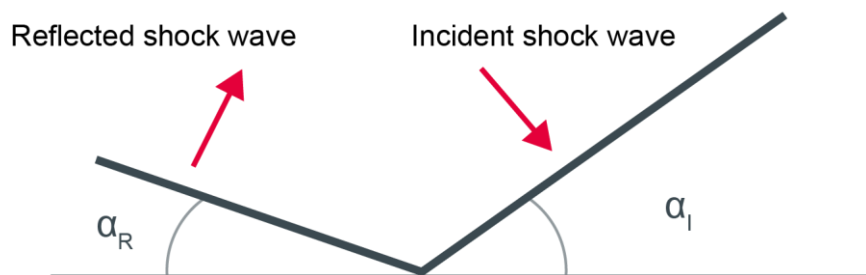


Figure 9-21 Angle of incidence, α_I , and reflection, α_R , of a shock wave hitting a surface

Table 9-3 Pressure Enhancement Due to Blast Wave Reflection at an Angle⁽¹⁷⁾

Angle of incidence of the blast wave α_i (degrees)	Enhancement factor
90*	1.00
80	1.48
70	1.95
60	2.43
39	2.80

* At an angle of 90° the pressure measured is called the incident overpressure (see section 9.3.4.5).

9.3.4.4 Mach Reflection

When a shock wave hits a surface, e.g. the ground, at an angle greater than a critical angle of approximately 39°, then Mach reflection can occur. The actual value of the angle depends on, inter alia, the peak overpressure.

When a spherical shock wave hits a surface, the first part of the shock wave hits the surface normal to the surface. Normal reflection occurs and the shock wave reflects back normal to the surface, Figure 9-22, point 1. As the spherical shock wave moves across the surface the angle of impact increases and the shock wave hits the surface at an angle and regular reflection occurs, Figure 9-22, point 2. The reflected shock wave has a higher pressure and hence higher velocity than the incident shock wave. As a result the reflected shock wave catches up with the incident shock wave. The two wave fronts merge and form a single front called a Mach stem, Figure 9-22, point 3. The Mach stem is perpendicular to the ground and forms a cylindrical front, expanding outwards. The Mach stem has an increased overpressure and impulse. This is called a 'Mach reflection'. The point at which the incident wave, the reflected wave and the Mach front ('Mach stem') meet is called the triple point and is illustrated in Figure 9-22, point 4. The height of the Mach stem will increase as it moves outwards away from the initial point of impact with the ground.

The Mach reflection is exploited to increase the blast damage from nuclear weapons by optimising the height of burst above ground level. Also Mach reflections will occur when explosions occur in proximity to large buildings.

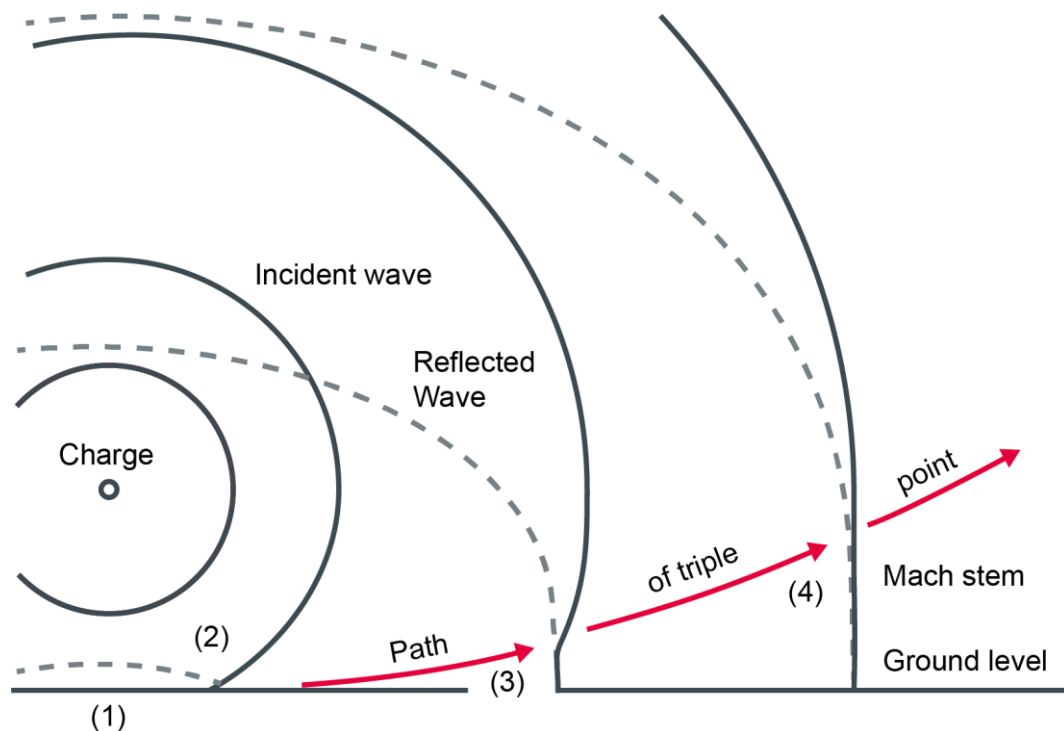


Figure 9-22 Mach Reflection

9.3.4.5 Incident overpressure

If α_i in Figure 9-21 is 90° then a pressure measured on a surface would be the incident peak overpressure. This is a blast wave travelling across a surface as shown in the Powerpoint slide [Incident and reflected blast waves](#) (go to Slide Show and click through the animation). Measurement and calculation of explosion blast effects are made to give baseline values for fully incident and fully reflected blast waves since, as has been demonstrated, the blast parameters will vary with reflected angle.

9.3.5 Effect of Altitude

As altitude increases, the density of air decreases and this reduces the effect of the blast wave. The decrease in blast strength with altitude is shown in Table 9-4, where A is the ratio of the charge weight, W_h , to produce a given overpressure at altitude, (h) , and the charge weight, W_o , to produce the same overpressure at sea level. As an example it can be seen that at an altitude of 9,100 m, 1.2 times the amount of explosive is required than would be used at sea level to achieve the same blast. Scaling of blast waves at different altitudes can be carried out using Sachs scaling⁽¹⁸⁾.

Table 9-4 Blast Attenuation at Altitude.

Altitude		Attenuation Factor
Feet	Metres	(A)
sea level	sea level	1.0
30,000	9,100	1.2
45,000	13,700	1.4
60,000	18,300	1.8
100,000	30,500	2.2

9.3.6 Explosions in a Confined Space

If an explosive detonates in a confined space, such as a room, two effects occur. First the blast wave is reflected from the walls, floor and ceiling of the room. This results in multiple reflected shock waves being experienced at any given position within the room. Secondly unless the pressure created by the production of hot gases by the explosion is vented immediately, e.g. through broken windows, blown out doors, etc. then there is a build-up of ambient pressure within the confined space called quasi-static overpressure. Where explosion accidents may occur such as in manufacture it is common practice to include blow-out panels in production rooms to assist in pressure release. Even so, on an explosive timescale the pressure release is not immediate and there always will be some quasi-static pressure effect that can last for hundreds of milliseconds. In the open a blast wave passes a given point in a few milliseconds and there is no further loading on a target.

If an explosion occurs within a tunnel where the blast wave cannot expand or escape then it will travel down the tunnel losing little energy from the shock front until it encounters side tunnels or branches such that the energy then can partition among the potential ways it can expand. Given the opportunity it may reflect back towards the source, which will take energy from the progress of the blast wave.

9.4 FUEL-AIR EXPLOSIONS

9.4.1 Creation of a Fuel-Air Explosion

A fuel-air explosion requires the pre-mixing of a fuel material, which can be in the form of a gas, liquid aerosol or fine powder, as a large volume cloud in air, which is a variant of the fuel-oxidiser mixture type explosive. These conditions, particularly with gases, can be created easily and have caused many explosion accidents both in domestic and industrial settings. Homes have been totally demolished by natural gas explosions due to gas leaks and the devastation of the Nyproplant at Flixborough, UK in 1974, which killed 28 people due to the

explosion of an estimated 36 tonnes of cyclohexane vapour in air, are both examples of the damage potential of fuel-air explosions.

9.4.2 Explosive Performance

The potential to produce damaging blast through a fuel-air explosion has been recognised by weapons designers. Conventional explosives such as TNT contain both the fuel and oxidiser elements within the explosive charge whereas a fuel-air warhead need only contain the fuel, as the oxidiser is oxygen in the air obtained at the point of initiation. A greater release of energy can therefore be achieved at the target for a weapon of given payload. It can be seen from Table 9-5 that the energy advantage can be as high as 10 times in ideal conditions compared to the heat of explosion of TNT at 4.2 MJ kg^{-1} . All but one, ethylene oxide also known as oxirane, are normally found in the gaseous state and not suitable for inclusion in a warhead. Oxirane has a boiling point of 10.5°C and is a liquid if kept under modest pressure.

Table 9-5 Heats of Explosion of Some Fuels

Fuel	Heat of Explosion (MJ kg^{-1})
Methane	50
Propane	49
Acetylene	48
Ethylene	47
Ethylene oxide (oxirane)	28

At first sight the TNT equivalence would appear to be almost an order of magnitude, however, an efficiency factor must be considered. The explosive potential of a fuel-air explosion can be expressed as shown in Equation (9-13) where K is the efficiency of explosion, W_F is the weight of fuel, ΔH_F is the heat of explosion of the fuel and ΔH_{TNT} is the heat of explosion of TNT.

$$W_{\text{TNT}} = (K \cdot W_F \cdot \Delta H_F) / \Delta H_{\text{TNT}} \quad (9-13)$$

The full heat of explosion of the fuel is only realised when it is mixed with the stoichiometric quantity of oxygen. In any real fuel-air cloud there will be a wide range of concentrations so that the full energy output will not be achieved. Additionally, since air contains only 21 % of oxygen, for every unit mass of oxygen in the fuel-air system there will be 3.7 units of nitrogen which dilutes the system and absorbs heat. The explosive efficiency is therefore generally found to be less than 40 %. Nonetheless, this still equates to a potential TNT equivalence of ~4.

A fuel-air cloud will provide the optimum blast with a stoichiometric mixture as described above. If the mixture varies either to a fuel rich or fuel lean (poor) mixture it will still produce an explosion until it reaches certain limits called Upper Explosion Limit (UEL) and Lower Explosion Limit (LEL). Table 9-6 gives

some examples of these limits for an explosion caused by deflagration (burning) and within these are a narrower set of limits inside which the mixture is capable of detonation. Figure 9-23 shows how detonability varies with stoichiometry and initiation energy. The unusual fact that the UEL of acetylene is 100 % and has the potential to cause an explosion with no oxidiser present is through it undergoing a rearrangement of 3 acetylene molecules to form benzene with a large negative heat of reaction. For this reason acetylene cylinders do not contain compressed gas but contain acetylene dissolved in acetone solvent.

Table 9-6 Some UEL and LEL Values

Fuel	Explosive limits % vol/vol in air
Acetylene	2 - 100
Oxirane	3 - 80
Hydrogen	4 - 76
Carbon monoxide	13 - 74
Diethyl ether	2 - 48
Carbon disulphide	2 - 44
Ethylene	3 - 34
Methane	5 - 14
Propane	2 - 10
Gasoline	2 - 8

Initiation can be thermal (igniferous/flame), electric discharge (spark) or explosive shock (booster charge) and the initiation energy influences the Explosion Limits. As initiation energy increase the limits become wider as shown in Table 9-7 for the electric spark initiation of a methane-air mixture. The closer the mixture to stoichiometry and the greater the initiation energy the more likely the cloud is to detonate as shown in Figure 9-23.

Table 9-7 Explosion Limits for Spark Initiation of Methane

Ignition Energy (J)	LEL % vol/vol	UEL % vol/vol	Range % vol/vol
1	4.9	13.8	8.9
10	4.6	14.2	9.6
100	4.25	15.1	10.8
10,000	3.6	17.5	13.9

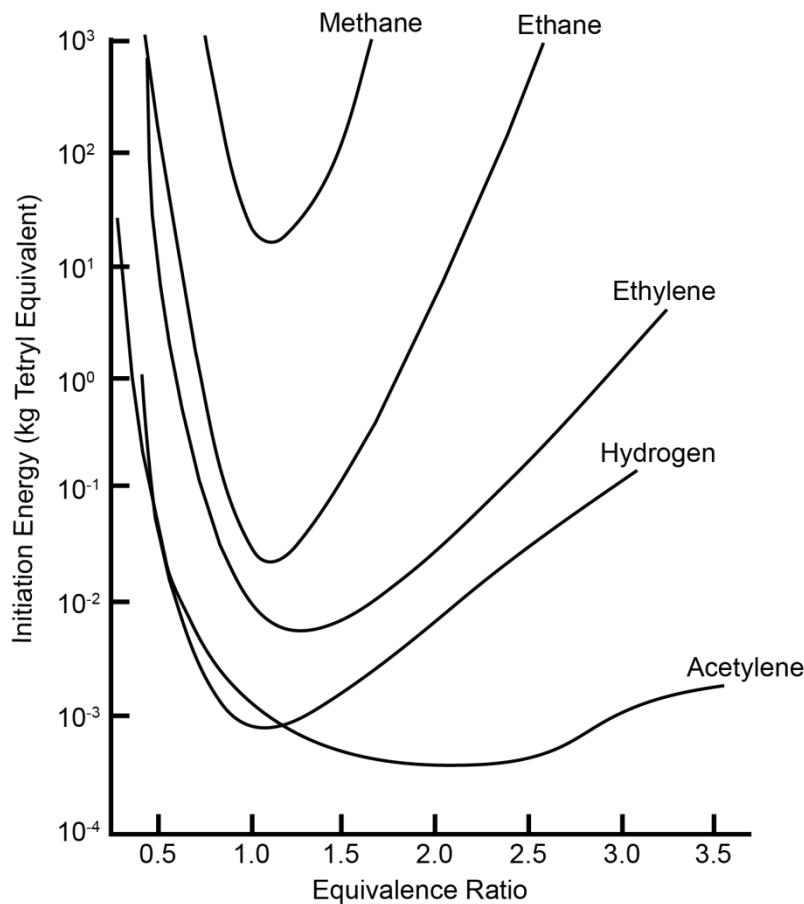


Figure 9-23 Detonability limits for some fuel-air mixtures

9.4.3 Fuel-Air Munition Effectiveness

9.4.3.1 Munition design and deployment

The basic design of a fuel-air munition is a cylindrical container filled with liquid fuel, examples being ethylene oxide or propylene oxide, which contains a central cylindrical burster charge filled with conventional high explosive. When the burster charge detonates the liquid is driven out in to a pancake shaped cloud of droplets and vapour creating the fuel-air mixture. The munition deploys a detonator or detonators for redundancy inside the cloud and when the fuel-air cloud is fully formed these initiate detonating the cloud. Vapourisation of the droplets primarily takes place when they are heated by the arrival of the shockwave or flame front following initiation of the fuel cloud.

The mass of the burster charge to fuel ratio have little effect on cloud dimensions once the ratio exceeds 1:40. The delay time between dispersion and cloud initiation of a few hundred milliseconds means that local meteorological conditions have little effect on cloud formation. Cloud sizes for

the dispersion of various quantities of propylene oxide (methyloxirane) in vertically aligned cylindrical drums fitted with central burster charges with a charge to fuel ratio of 1:20 are shown in Table 9-8. The cloud height and diameter varies little between 100 m and 200 m after dispersion and fuel concentrations ranged from 56 g m^{-3} - 105 g m^{-3} (stoichiometric value 100 g m^{-3}).

Table 9-8 Dimensions of Methyloxirane Clouds

Fuel quantity (litres)	Cloud diameter (m)	Cloud height (m)
10	10.6	1.8
30	13.9	2.5
45	16.0	2.9
60	17.6	2.9
150	20.0	3.8
170	23.5	3.7
300	25.1	5.1

9.4.3.2 Blast Effects

For fuel-air clouds that detonate the detonation pressures and velocities within the cloud are much lower than those of condensed explosives with maximum values of 2000 kPa (20 bar) and 1800 m sec^{-1} (c.f. TNT 19 MPa and 6950 m sec^{-1}) so they have little brisant or shattering effects against hard targets. The value of a fuel-air warhead is to be found in the propagation of airblast. When a condensed explosive charge detonates it may be regarded as a point source of energy. The blast overpressure associated with the explosion falls rapidly with increasing distance from the charge. By contrast the source for a fuel-air explosion is in the form of a large cloud which, as an example, for a 30 kg charge, may be 15 m in diameter.

Therefore, if a fuel-air warhead is detonated at ground level there will be a blast pressure of up to 2000 kPa (20 bar) under the whole cloud. In comparison, if a 30 kg TNT warhead is detonated at ground level the blast peak pressure will have dropped to ~2000 kPa at a distance of 2.5 m and at 7.5 m, the radius of the cloud described above, it will be 185 kPa. Furthermore, when the blast wave leaves the edge of the cloud the blast peak pressure decays less quickly than from a point source and overpressure duration will be longer maintaining impulse. Together these factors make a fuel-air warhead an extremely effective blast weapon.

9.4.3.3 Fuel-air weapons

Both the US and Russia have included fuel-air weapons in their arsenal. The US had particular interest in the use of such weapons to clear minefields such as Surface Launched Fuel Air Explosive (SLUFAE) and Catapult Launched Fuel Air Explosive (CATFAE) developed in the 1970s and 1980s. However, they proved not to be sufficiently effective at detonating mines or clearing wire obstacles and were withdrawn from service. Large air dropped bombs such as the 500 lb BLU-95 and the 2000 lb BLU-96 and cluster bombs CBU-55 and CBU-72 have all been withdrawn from service.

It is understood that Russia field a range of fuel-air weapons including air dropped bombs, cluster munitions, multiple launched rocket systems, helicopter launched missiles and aircraft missiles. The BM-30 Smerch is of particular note as probably the most effective fuel-air weapon. It consists of a 12 barrel 300 mm calibre multiple launch rocket system with a range of up to 70 km that, with a full salvo, covers a target area of over 0.5 km². This weapon has been sold to over a dozen countries worldwide.

9.4.3.4 Terminology

There has been some confusion regarding the names given to weapons that utilise oxygen from the air as an explosive component, which began with the introduction of the Russian shoulder launched missile known as RPO-A. This was called a thermobaric weapon and the term began to be used for both this new type of warhead and fuel-air warheads. Adding to the confusion was the use of the term 'volumetric warhead' and more recently 'enhanced blast warhead'. These various terms are explained below:

- A **Fuel-air Warhead** is a container of liquid fuel with a central high explosive burster. The central burster is detonated and causes the fuel to mix with air in a pancake shaped cloud. A few hundred milliseconds later detonators thrown in to the cloud during initial functioning detonate the fuel-air cloud. This is clearly a 2 stage event.
- A **Thermobaric Warhead** contains an explosive charge consisting of an explosive capable of detonation but mixed with a large percentage of metal powder such as aluminium. Unlike the Torpex explosives where the metal content is limited the thermobaric explosive may contain a much higher percentage as this reacts with air as the detonation products expand adding to the heat content of the explosion. This is a single stage event as there is only one detonation although it does utilise oxygen from the air. RPO-A has in the past been labelled as a Flame Weapon even in its country of origin. This is likely to come from the fact that the RPO shoulder launched missile was truly incendiary in its effect. There is no doubt that RPO-A is a blast weapon.
- A **Volumetric Explosion** is one where oxygen from the air is a major contributor to the energy of explosion. A fuel-air explosion, therefore, clearly is 'volumetric', but there can be a case to say that a Thermobaric

Explosion is also volumetric to some degree. It is generally accepted that only a Fuel-air Explosion is truly a Volumetric Explosion.

- An **Enhanced Blast Warhead** is one designed to maximise the blast output. The term 'enhanced' would presuppose a baseline, however, it can be said that blast enhanced explosives have developed since the use of picric acid as a warhead filling changed to TNT as shown in Figure 9-24.

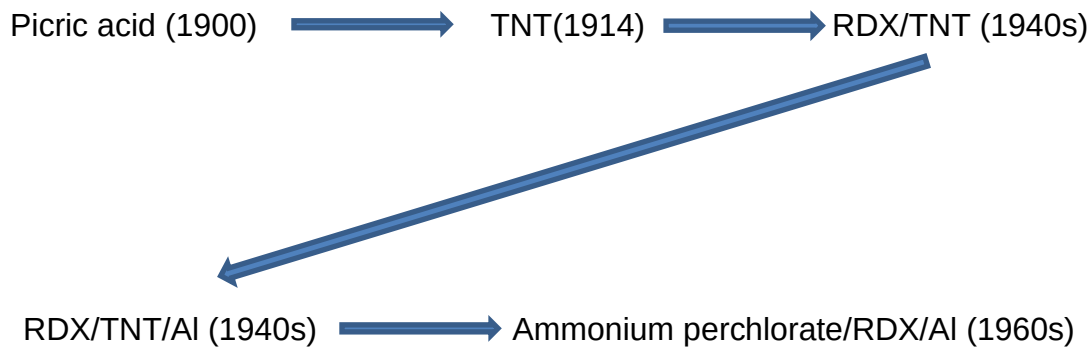


Figure 9-24 Development of blast enhancing explosives

Based on the information in section 9.4.3.2 it could be said that a fuel-air warhead was an Enhanced Blast Warhead. However, the current use of the term Enhanced Blast covers the use of formulations with large percentages of metal powder that react with oxygen in the air to increase the heat energy from the explosion and to an extent increase the duration of the blast pressure. Another name for these is Metal Augmented Charges (MAC).

Therefore, Thermobaric Warheads are Enhanced Blast warheads and vice versa. In the UK the term Enhanced Blast is used and not Thermobaric as the latter has humanitarian connotations with the unfounded but nonetheless popular believe that they are incendiary weapons. This type of warhead is particularly effective inside enclosed spaces such as buildings and tunnels. The UK employs such warheads in anti-structure munitions.

9.5 EXPLOSIONS UNDER WATER

9.5.1 Detonation Under Water

The detonation of an explosive in water is not fundamentally different from detonation in air or in any other compressible medium. In all cases the event involves the propagation of a primary shock from the explosive charge in to the surrounding medium followed by the slower expansion of the gaseous products of explosion. The way in which the total energy of the explosive charge is partitioned between them depends on the nature of the medium and on the properties of the explosive. The energy distribution can be calculated from

theory and in the case of water, it can also be determined experimentally because the separation of the two effects, primary shock wave propagation and gas expansion, is much more complete in water than in air. For an in depth understanding of explosions in water read the text by Cole⁽¹⁹⁾.

9.5.2 Shock Wave Effects

In air, which is a medium of low density and high compressibility the primary shock wave is comparatively short-lived. It decays rapidly due to energy lost by irreversible heating of the air. As the hot, high pressure gaseous products expand immediately behind the primary shock wave that deposited heat energy is captured and contributes to the energy undertaking work compressing the surrounding air, which produces the blast wave. Thus beyond a few charge diameters from the explosion centre there is only one pressure wave to be considered.

In water the transmission of shock wave energy is much more efficient because water is some 800 times more dense than air and its compressibility is correspondingly much less. Even so, at the very high shock pressures initially produced on detonation, some energy is lost by inelastic compression of the water.

This efficient transmission of the shock wave allows it to detach and travel away from the expanding gases. When a spherical charge of high explosive, centrally initiated, detonates at moderate depth in deep water, the corresponding spherical shock front travels radially through the charge and into the surrounding water. The water at the interface with the explosive is violently compressed and accelerated. The shock wave thus formed is propagated through the water at up to 5000 m s^{-1} , becoming totally separated from the gas bubble which is expanding relatively slowly behind it. The velocity then decreases quickly to the sonic velocity in water of about 1500 m s^{-1} .

The shock pressure within the explosive charge may be more than 250 kbar but the acoustic impedance mismatch at the interface of the detonation products and the water causes a rarefaction wave to be reflected back into the detonation sphere. Because of this the initial shock wave pressure is approximately one half of the detonation pressure, say 125 kbar. The difference between shock pressures in air and water from identical explosive charges is shown in Figure 9-25.

Under reasonably good conditions an observer above the water surface can see the manifestation of these separate effects. The primary shock wave from the detonating charge can be seen fleetingly as a rapidly expanding ring of apparently darkened water, often called the 'slick'. This ring is caused by the reflected shock wave pressure momentarily flattening ripples on the surface. Directly above the explosion point, if it is not too deep, a dome of spray appears due to spalling of the water surface as the primary shock wave is reflected. Finally comes the plume of water thrown up by the gas bubble

venting at the surface. The shape and size of the plume varies with the depth of the explosion, and a charge at great depth does not create one. These observations will be difficult to separate if the explosion takes place in shallow water.

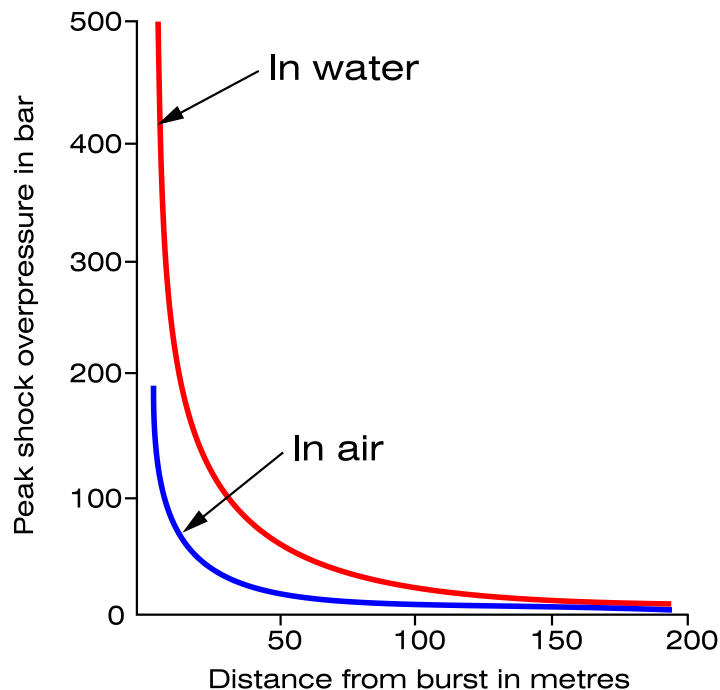


Figure 9-25 Peak shock pressure versus distance in air and in water for a spherical 136 kg charge

9.5.2.1 Shock wave pressure profile

The pressure of a shock wave in water decays rapidly over a time scale of about 1 ms. This decay time initially follows an exponential law so that at time, (t), after the arrival of the shock wave at a point of distance, (L) from the charge centre the shock wave pressure, (p), is given by:

$$p_t = p_{\text{Max}} \cdot e^{(-t/\theta)} \quad (9-14)$$

Where θ is the time decay constant (Figure 9-26). For a 136 kg TNT charge q was found to be 0.5 ms at a distance (L) of 6.1 m, and 0.9 ms at a distance (L) of 152 m; the corresponding values of p_{max} were 424 bar and 7 bar respectively. Explosives of higher detonation pressure than TNT (e.g. RDX and HMX compositions) give shorter time constants, indicative of a more rapid thermal dissipation of the shock wave energy by adiabatic and kinetic work on the water medium. Lower performance ammonium nitrate based explosives have longer time constants.

In a high pressure shock wave the dissipation of energy can be quite considerable. For example, a 300 kbar shock propagating through water loses

4.2 W for every cubic centimetre of water traversed, whereas at low shock pressures the losses are much less, only 0.12 W cm⁻³ for a 25 kbar shock. The energy density of the wave falls with distance from the charge due to its spherical divergence.

Primary shock wave pressures are virtually independent of depth and decay less rapidly than in air (Figure 9-26). It may be inferred from this that primary shock waves in water have a greater radius of effectiveness than shock waves in air. The positive duration of waterborne shock waves is, however, much less than for airborne shocks so that the impulse integrals are not excessive when compared with the same charge weight detonated in air at the same distance.

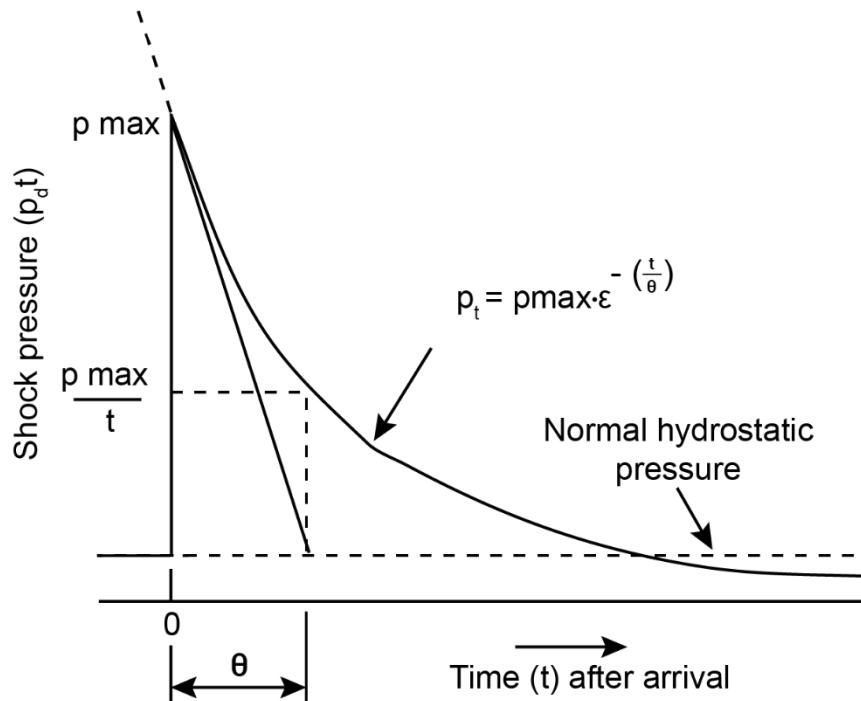


Figure 9-26 Shock pressure versus time, for an underwater shock wave

9.5.2.2 Scaling of shock parameters

The peak shock pressure and some other parameters of underwater shock waves obey the 'principle of similarity' known as Hopkinson's law.

9.5.2.2.1 Distance

The fall-off of peak pressure, $p_{\max}$, with distance is very steep close to the detonating charge, approximating to an inverse cube relationship within 5 charge radii of the charge. A simple inverse relationship holds well however, between about 10 to 100 charge radii.

$$P_{\max} \propto 1/L \quad (9-15)$$

9.5.2.2.2 Charge weight

Peak pressure is found to vary approximately as the cube root of the charge weight giving an overall empirical equation for the peak pressure of:

$$P_{\max} = k \times (W^{1/3} / L)^A \quad (9-16)$$

A is an index which has the value of 1.16 for TNT and varies slightly for other explosives. k is a constant depending on the detonation parameters of the explosive and is usually expressed relative to the standard TNT (density 1.52 g cm^{-3}) for which it has a value of 510, giving $P_{\max}$ in bar. For other explosives, k_x may be found by:

$$k_x = k_{\text{TNT}} \times p_x / p_{\text{TNT}} \quad (9-17)$$

Where p_x and p_{TNT} are the respective Chapman-Jouguet (C-J) detonation pressures. The equation applies at short distances from the charge. At distances of a few charge radii outwards dissipation of the shock wave energy is such that the pressures are determined largely by the total energy of the charge, thus:

$$k_x = k_{\text{TNT}} \times Q_x / Q_{\text{TNT}} \quad (9-18)$$

9.5.2.3 Shock Impulse

Shock impulse (I), is obtained by integrating the shock pressure with respect to time:

$$I = \int_0^t p \cdot dt \quad (9-19)$$

The impulse (and shock wave energy) integrals are conventionally taken to $t = 6.7 \text{ q}$ and may be expressed by:

$$I_{6.7} = k_I \times W^{1/3} \times (W^{1/3} / L)^B \quad (9-20)$$

Where B is 0.89 for standard TNT and K_I is 57.4 for a result in bar ms.

Figure 9-27 shows the time dependence of the pressure and impulse.

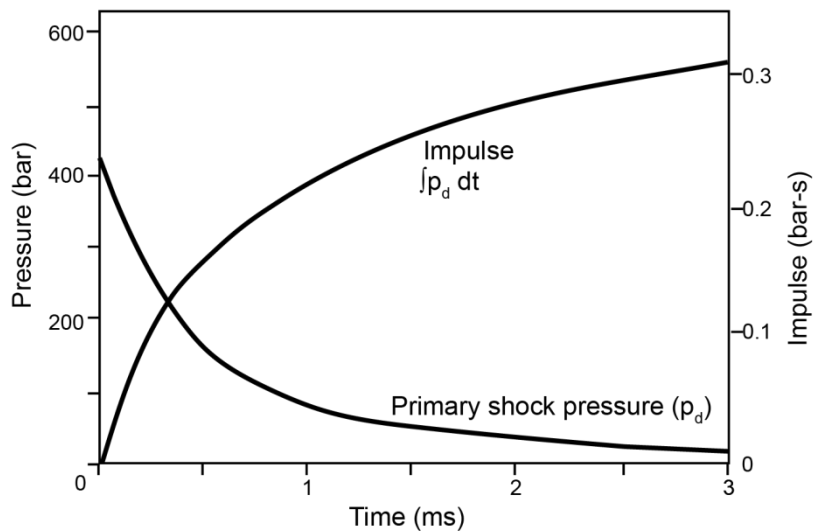


Figure 9-27 Increase in impulse from latter portion of shock wave, as recorded at 6.1 m (20 feet) from a 136 kg TNT charge

9.5.2.4 Shock-wave energy density

The shock wave energy density E_s is the (pressure)² - time integral and is directly related to the chemical energy Q of the explosive.

$$E_s = \int_0^t p^2 dt \quad (9-21)$$

It may be evaluated from the empirical equation:

$$E_s = k_E \cdot W^{1/3} (W^{1/3} / L)^E \quad (9-22)$$

Where: E is 2.05 for standard TNT and k is 0.0343 for a result in $J m^{-2}$.

9.5.3 Underwater Bubble Effects

A charge detonated under water creates a more or less spherical bubble of gas inside which the pressure immediately after the departure of the primary shock wave is very high. This high pressure causes the bubble to expand rapidly in spite of the inertia of the surrounding water, and is aided by the 'after flow' of the water in the wake of the primary shock wave. The pressure in the bubble falls as expansion occurs and as the temperature of the gas falls due to

adiabatic expansion. Because of the inertia of the water being displaced, the bubble continues to expand even though its pressure begins to fall below the hydrostatic pressure. Expansion soon ceases and a rapid contraction begins until the in-flowing water has compressed the bubble to a higher pressure than the hydrostatic pressure and so the cycle of expansion and contraction begins again.

In this manner a series of bubble oscillations of decreasing amplitude follows, numbering up to ten or so. Considerable flow of water accompanies the bubble oscillations and velocities as high as 100 m s^{-1} may be imparted to the water. The kinetic energy of this high velocity water is a potent source of damage to structures within two or three bubble radii.

Additionally, each bubble oscillation generates a quite separate pressure pulse which is set up at the point of maximum recompression of the bubble, when the water flow is reversing (Figure 9-28). The series of pulses grows successively weaker and only the first one or two are of significance.

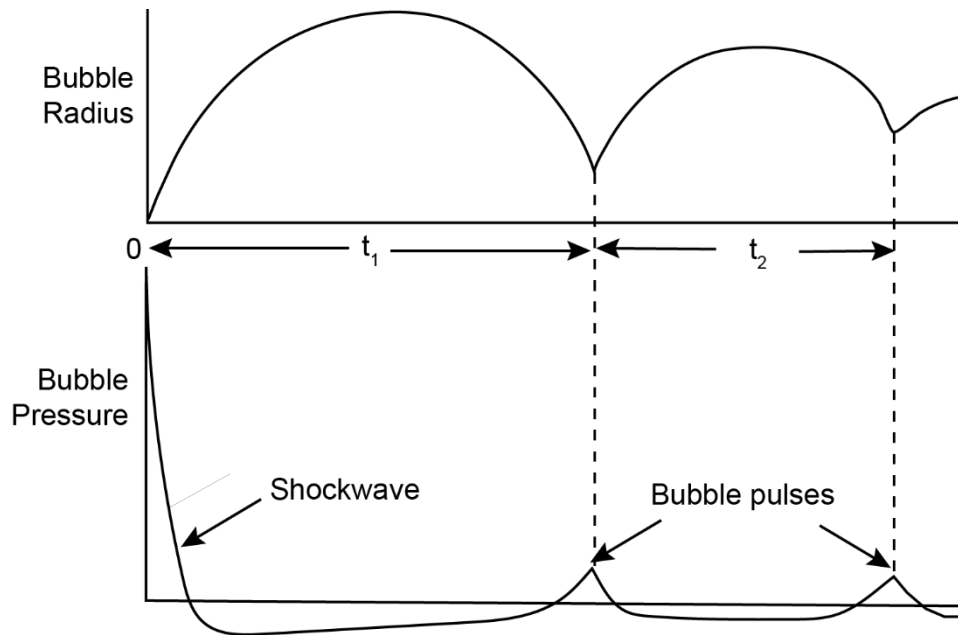


Figure 9-28 Gas bubble pulsation and pressure sequence

The timescale of the bubble period is long in relation to the duration of the primary shock wave. For example, a 250 g Tetryl charge detonated at a 91 m depth generates a bubble which reaches its maximum radius in 14 ms and its minimum radius in 28 ms. It is evident therefore that an interval of tens of milliseconds will occur between the primary shock wave and the first bubble pulse. The interval increases with distance from the charge due to the falling velocity of the bubble pulse with distance.

The peak pressure in a bubble pulse is very much lower than the peak shock pressure from the same charge at a given distance. For example, a 136 kg TNT charge at a depth of 20 m generates a primary shock wave pressure at a

distance of 18.1 m of 130 bar compared with a first bubble pulse of 5 bar at the same point. However, the longer duration of the bubble pulse enhances the magnitude of its impulse integral so that it can exceed that of the primary shock wave at some distances.

9.5.3.1 Mathematical formulae for the calculation of bubble parameters.

9.5.3.1.1 Bubble radius

Maximum bubble radius b_{max} depends on charge weight W , explosive power index, and hydrostatic pressure depth h (all dimensions in metres or kg) such that:

$$b_{max} = \frac{k_b \cdot W}{(h + 10)^{1/3}} \quad (9-23)$$

k_b is related to the explosive power index of the explosive by the formula:

$$k_b = \frac{\text{power index of explosive}}{\text{power index of TNT}} \times 3.42 \quad (9-24)$$

for a result in metres and kilograms.

9.5.3.1.2 Bubble period

The period of the first bubble oscillation t_1 (in seconds) for TNT is given by:

$$t_1 = 2.1 \times W^{1/3} / (h + 10)^{0.83} \quad (9-25)$$

9.5.3.1.3 Bubble energy

The theory of underwater bubble behaviour shows that the total energy E_b , associated with the radial outflow of water due to bubble expansion is given by:

$$E_b \approx \frac{4}{3} \cdot H_0 (b_{max})^3 \quad (9-26)$$

Where H_0 is the normal hydrostatic pressure (consistent units must be applied).

9.5.3.2 Bubble migration

Because an explosion bubble pulsates it does not rise to the surface steadily and vertically under the influence of its buoyancy. Instead, the varying resistance to motion that it experiences due to its changing size and the associated water flow around it will cause it to:

- a. migrate towards any nearby rigid boundary (e.g. a ship, dam or sea wall)
- b. to rise to the surface in an uneven manner

This behaviour is illustrated in Figure 9-29.

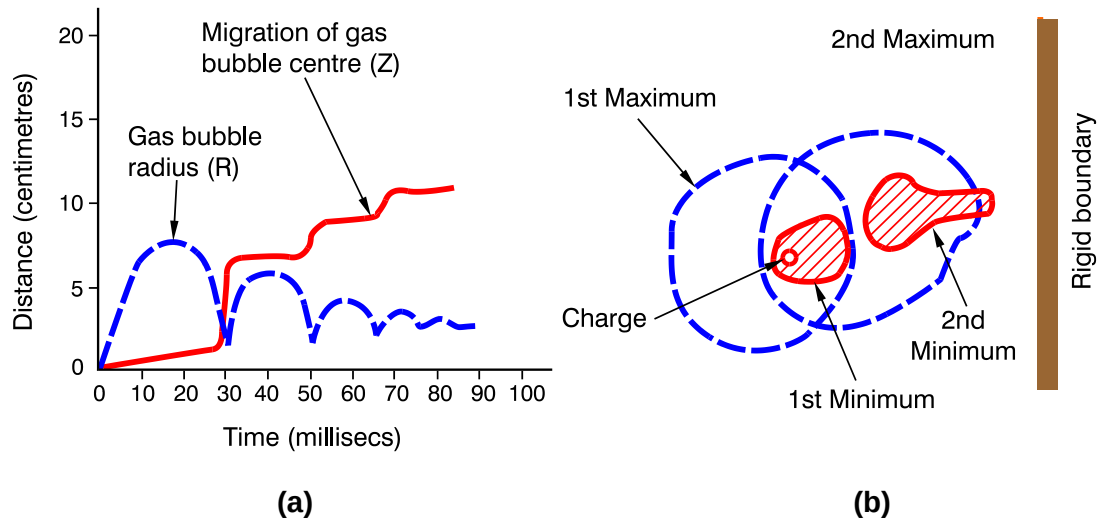


Figure 9-29 Migration of bubble upwards (a) in open water and (b) towards a rigid boundary

9.5.4 Damage by Underwater Explosions

The way in which damage is caused to underwater structures, particularly the hulls of ships and submarines, by explosive charges is a complex subject involving questions of materials science, engineering and fluid dynamics as well as the effect of incident and reflected shock waves in water. The topic is therefore largely outside the scope of the present work and is represented here by a few general remarks in conclusion.

The underwater attack of vessels by explosives usually involves the detonation of the charge virtually in contact with the hull, e.g. in the cases of torpedoes and sea-mines with contact fuzes, or limpet charges. Where this is so, the detonation pressure of the explosive is exerted almost undiminished on the plating, which is then likely to be fractured and to be further distorted by the rapid flow of water associated with bubble oscillation. Experience has shown, however, that greater damage is inflicted when there is an intervening stand-off distance between the charge and the hull. In this situation the effects of the primary shock wave and the bubble oscillations are separated by time and there is a question as to which of them is the deciding factor in damage capacity.

It is seen from Figure 9-30 that the shock wave energy available for inflicting damage is some 33 % of the total explosive energy (this applies to a short stand-off distance), whereas the first bubble pulse accounts for only 13 %. It would appear, therefore, a priori, that damage by shock wave is more likely than damage by bubble pulses. Account must be taken, however, of the kinetic

energy of the mass of moving water associated with the bubble oscillation. For a large bubble envelope moving at some 100 m s^{-1} the kinetic energy imparted to the target by this water flow can be very destructive, involving as it does an impact followed by a suction effect. The bubble oscillations also create pressure pulses of relatively long duration which cause additional stresses in the target material.

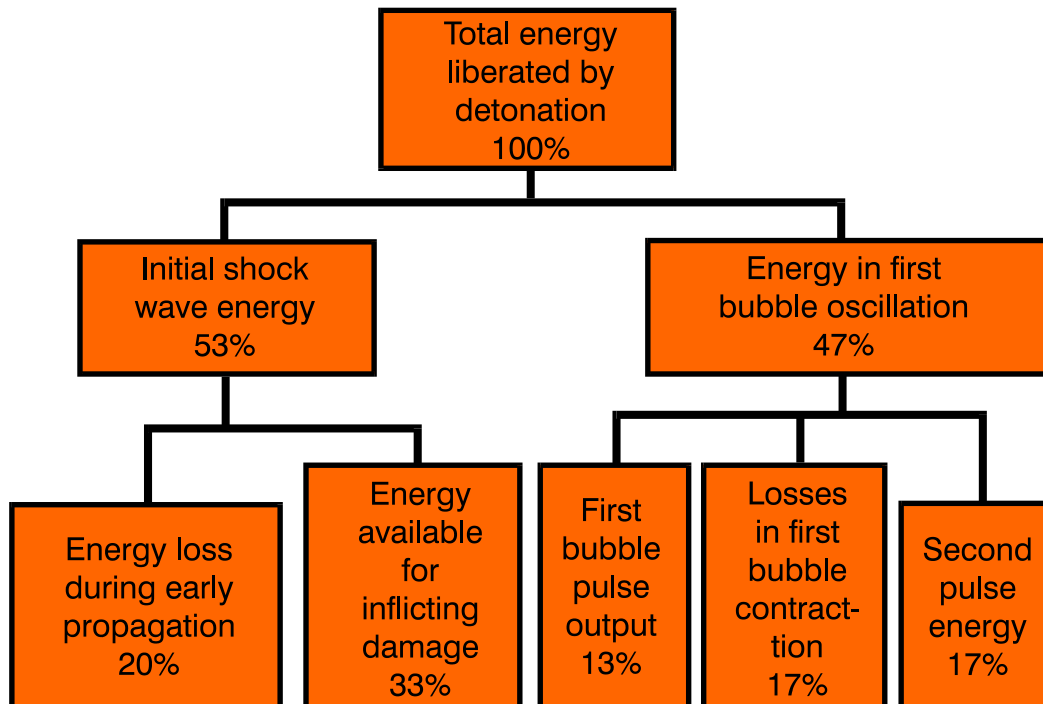


Figure 9-30 Typical distribution of the energy of an underwater explosion

The damage capacity of the shock wave depends, as in the case of airblast, on its duration as well as its maximum pressure, and this must be matched to the response time of the target, in this case plating backed only by air. The response time will depend on several factors, including the area of air-backed plating, which is effectively governed by the spacing of the supporting structure of the hull. The area of plating exposed to the shock wave at angles of incidence near to normal will be greater if the charge is detonated at some distance of stand-off, due to the radial progress of the wave. It is therefore generally true that, for large charges, the most effective position from which to attack a ship's hull is at an optimum stand-off depth below amidships. The damage done to an area of plating by the spreading of shock wave will then be exacerbated by the upward migrating bubble oscillating in contact with the damaged plating.

In the case of submarines the nature of the hull design produces a more resistant target. Moreover, the relative contributions to damage infliction which are made by primary shock, bubble oscillation and bubble pulses at the depth of a ship's draught are considerably different at the greater depths where

submarines normally operate. Bubble effects are much reduced, and the damage capacity of the explosive charge depends much more on the primary shock which it creates. In one respect the vulnerability of a submarine is greater compared with a ship, since its hull structure is subjected to greater environmental stress at depth. These and other complicating factors make the generalised prediction of damage susceptibility even more difficult in the case of submarines than for ships.

For both ships and submarines, if the duration of the shock wave is much shorter than the deflection time of the plating, primary damage will not occur but there will still be a considerable vibration set up throughout the vessel. The plating can be accelerated at up to 10^5 g (10^6 m s^{-2}) and the structural members at a tenth of this figure. The vibration can last for some tens of milliseconds, depending on the duration and impulse of the shock wave. The rapid and irregular vibration thus caused can damage the delicate internal components on which a modern ship relies for its fighting effectiveness.

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Appendix A Units of pressure

The SI unit for pressure is the Pascal (Pa). Other units commonly used include the atmosphere, bar, psi (pounds per square inch) and for lower pressures, particularly from guns, the decibel. A list of the conversion factors is given in Table 9-9.

Table 9-9 Conversion of Pressure Units to Pascals

Unit	Value in pascals
bar	100,000
atmosphere	101325
psi (pounds per square inch)	6894.76
decibel (dB)	$\text{Pressure (Pa)} = 0.00002 \times 10^{\text{Pressure(dB)}/20}$