THE EFFECTS OF EXPLOSIONS

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In this general review the propagation of ideal shock waves in air is outlined, together with the scaling laws which make it possible to estimate parameters from standard data. Propagation in water and in the ground are also described. The loading of structures by incident shock waves is given together with empirical data on the response of various structures to blast. Finally the topic of blast from exploding large unconfined clouds is reviewed in the light of experience, experiments and current theoretical treatments.

INTRODUCTION

The effects of explosions at a distance are those due to shock waves in air, the ground or in water. In respect of major hazards the region of principal interest is the field somewhat remote from the origin. It is not proposed therefore to deal with close-in effects such as cratering and damage caused in the immediate vicinity of the explosion.

First, propagation of shock waves in air, the ground and in water will be considered. In respect of propagation in air in particular there is considerable difference between that from a condensed explosive and that from a large, unconfined cloud, so these will be considered separately.

Second, the interactions of shocks with structures will be outlined, to define the loading to which a structure may be subjected, and the consequences.

SHOCK WAVES IN AIR

A shock wave in air, whatever its initial structure, tends to transform itself into the stable form known as an ideal shock wave. This follows from the properties of air as a compressible gas. Regardless of the source the front of a pressure disturbance steepens as it travels through the air, a process known as peaking-up.

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In order to understand this it is necessary to note that the disturbance travels at a velocity dependent on the local velocity of sound and that the velocity of sound varies with the square root of the temperature. At the front the air is compressed adiabatically and therefore its temperature is raised. Behind the front the disturbance is moving into preheated air for which the sonic velocity is higher. Hence it moves faster and catches up with but cannot overtake the front.

In the case of the shock generated by a condensed explosive peaking-up occurs within a distance of a few charge diameters. Thus for most practical purposes at all distances more than a few feet from a condensed explosive, the disturbance may be treated as an ideal, or classical, shock wave.

Ideal Shock Wave

The characteristics of an ideal shock wave are described in the literature, for example by Kinney (1) and Baker (2).

At the front there is a discontinuity with an almost instantaneous change in pressure and temperature. Behind the front the pressure falls in a pseudo exponential manner to ambient and then continues to fall to give a negative pressure phase. The whole disturbance moves forward at a super-sonic velocity.

An important feature is that immediately behind the front the air is moving in the direction of travel of the wave with a characteristic velocity known as the particle velocity which is somewhat smaller than the wave velocity.

The parameters of the shock wave are interrelated by a set of simple equations which are derived from the properties of air and are independent of the nature of the origin of the shock except in respect of the total energy content.

Useful equations relating peak overpressure, shock velocity and particle velocity are :-

$$P_x = 7\,(M_x^2-1)/6P_o \quad \ldots\ldots\ldots\ldots \quad (1)$$

$$M_p = 5\,(M_x^2-1)/6M_x \quad \ldots\ldots\ldots\ldots \quad (2)$$

Values for these, and other parameters of ideal shock waves have been determined for a given weight of standard explosive at different distances and are available in the literature, such as (1).

Scaling laws are means whereby the parameters for any given weight of standard explosive may be determined from those of the standard or tabulated values.

From equations such as (1) and (2) it is apparent that a shock wave can be specified by a single parameter. It is common practice to use the peak overpressure as the characterising parameter, from which, if required, the other parameters may be calculated.

The scaling law most frequently used is that put forward by Hopkinson (3) which states that two explosions will give identical blast waves at distances which are proportional to the cube root of their energies. This gives rise to the concepts of scaled distance, time and impulse, in terms of the cube root of the weight of explosive or energy.

$$\bar{D} = D/W^{1/3} \text{ or } D/E^{1/3} \quad \ldots\ldots\ldots\ldots \quad (3)$$

$$\bar{T} = T/W^{1/3} \text{ or } T/E^{1/3} \quad \ldots\ldots\ldots\ldots \quad (4)$$

$$\bar{I} = I/W^{1/3} \text{ or } I/E^{1/3} \quad \ldots\ldots\ldots\ldots \quad (5)$$

Experimental confirmation of these relationships has been obtained by many workers including Kennedy (4) and Dewey (5).

Thus if a plot is made of peak overpressure against scaled distance a curve is obtained which can be used for any weight of the same explosive or energy of detonator. In practice the standard explosive used for such plots is TNT. For other explosives a TNT equivalent is used based on energy yield.

Limitations of scaling laws. The cube root law as formulated by Hopkinson applies to ideal shock waves produced by explosions of the same explosive of different sizes but of similar geometry in the same atmosphere.

This immediately raises doubts whether it is applicable to a low density explosive such as a gas cloud, or to gross differences in geometry, e.g. to a line charge.

It would also not be applicable if there were altitude effects or other differences in ambient air conditions.

Sachs (6) and Sperraza (7) developed a scaling law which incorporates a term for the ambient air pressure and thus is particularly applicable in domains of low pressure :-

$$\bar{D} = P_o^{1/3}\, D/W^{1/3} \quad \ldots\ldots\ldots\ldots \quad (6)$$

where P_o is in atmospheres, D in feet and W in pounds of TNT.

Non-ideal Shock Waves

Although for most practical purposes it suffices to assume that the shock wave at distances more than a few charge diameters from the detonation of a condensed explosive is an ideal shock wave there are certain differences which have been observed.

The shock wave from an explosion near the ground is reflected to some extent by the ground. If the surface were infinitely hard so that reflection were perfect the strength of the shock wave would be double that over a perfect non-reflector. The reflectivity of the ground varies considerably. This may be one of the reasons for the considerable variations in the literature of pressures at a distance. In practice it is usual to assume perfect reflection, but reflectivity may vary from point to point in the field.

Observations made of shock waves from cased charges (that is explosives in substantial metal containers) frequently reveal a number of relatively small disturbances (commonly referred to as "trash") superimposed on the basic pressure curve. These are generally due to shocks produced by fragments of the casing.

An effect described by Bryant (8) is observed in very large explosions due to the effects produced ahead of the shock by heat radiation.

Shocks in the ground produced by the explosion travel faster than the airborne shock. They may generate shocks in the air which appear as precursors as described by Dewey (9).

Secondary and even tertiary shocks following the main shock are sometimes produced by the behaviour of the product gases after they have left the interface.

Larson and Olson (10) found that in the near field the pressure rise from the bursting of air-filled pressure vessels was far from ideal. The rate of rise of pressure was similar to the rate of decay. This is, of course, but one example of non-ideal shocks in the near field from a dispersed explosion. At greater distances the shock peaked up.

Propagation of Ideal Shock Waves in Air

The basic equations for shock waves were derived by Hugoniot (11) and Rankine (12). They are deceptively simple but exact analytical solutions are only possible for certain limiting conditions and restricted geometries.

One well known solution for strong shocks is that given by Taylor (13).

$$P_x = 0.155E/D^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

Important studies were those of Kirkwood and Brinkley (14) and of Neumann and Bethe (15).

Other solutions for particular initial conditions have been given by Oppenheim (16), Landau and Stanyukovich (17) and Zeldovich and Kompaneets (18).

Probably the most important are the two expressions derived by Brode (19) based on a method due to Neumann and

Richtmyer (20). These refer to domains of high and low pressure respectively

$$P_x = 657/\bar{D}^3 + 98 \ (\mathrm{KN/m^2}) \quad \ldots\ldots\ldots\ldots\ldots \quad (8)$$

$$\text{for } P_x > 100 \ \mathrm{KN/m^2}$$

$$P_x = 96/\bar{D} + 143/\bar{D}^2 + 574/\bar{D}^3 - 2 \ (\mathrm{KN/m^2}) \quad \ldots\ldots \quad (9)$$

$$\text{for } P_x \leq 100 \ \mathrm{KN/m}$$

where $\bar{D}$ is in $\mathrm{m/kg}^{1/3}$

Henrych (93) has produced a similar set of three equations.

A very considerable amount of practical data has been obtained from experiments and experience in the military field. Of these perhaps the most important are those obtained by Goodman (21) in respect of shocks produced by the detonation of pentolite; by Glasstone (22) and others.

Compilations have been made by Mills et al (23), Baker and Schuman (24), Lehto and Lutzky (25) and others.

More readily accessible are tabulated data and graphs to be found in Kinney (1), Petes (26) and in the handbook on the Hazards of Chemical Rockets (27). Of special interest is the compilation by Robinson (28) of data from 140 accidental explosions in U.K. and U.S.A. involving quantities of explosives from 14 pounds to 9 million pounds.

Additional data will be found in Stoner and Bleakney (29) who worked with small charges, but there is some doubt about the accuracy of their measuring devices; in Weibull and Enequist (30), in Fisher (31) and Hartmann (32). Kingery (33) gives data relating to large charges, up to 500 tons of TNT, as do Reisler et al (34) reporting Canadian tests at Suffield.

Study of all these data and unpublished official U.S. and U.K. data reveals that there are considerable differences in values given by different authors. In Appendix 2 I have plotted the upper and lower limits of the values. The differences between the two lines indicate the uncertainty in the true value or the unrecognised variations in the conditions of the tests. It is of interest that the values calculated from Brode's equations (8) and (9) lie on the lower pressure boundary of the plotted area.

Abnormal Propagation

The commonest cause of abnormal pressures, high or low, is the presence of buildings, trees or the like which either increase the pressure by reflections or decrease it by screening. Propagation data are based upon shock waves expanding spherically over plain ground without obstructions.

PROPAGATION IN WATER

Because of the very great differences in physical characteristics of air and water propagation of shock waves in water is quite different.

The three classical theoretical treatments are those of Penney and Dasgupta (43), Kirkwood and Bethe (44) and Kirkwood and Brinkley (45). The whole subject has been dealt with comprehensively in his classical book by Cole (46).

A useful compilation of published theoretical and experimental results is given by Enhamre (47) in his study of the effects of underwater explosions on elastic structures. His graphical representation is reproduced in the practical book on rock blasting by Langefors and Kihlstrom (48). Maximum pressure and impulse are plotted against scaled distances.

DeRaadt (49) derives an equation for the peak pressure from an unconfined underwater charge of TNT at a density of 1.52.

$$P_x = 555(W^{1/3}/D)^{1.13} \quad \text{Kgf/cm}^2 \quad \ldots\ldots\ldots\ldots \quad (10)$$

where the weight of explosive is in Kilograms and the distance is in metres.

In the case of an explosive in a shothole in underwater rock he estimates that the peak pressure is less than 10% of that from an unconfined charge.

During underwater blasting the shock wave may be significantly affected by reflections. Reflection from the surface water/air produces a negative shock which will tend to attenuate the tail-end of the direct shock wave whilst reflection from a hard bottom will tend to increase the effect.

An object close in to an underwater explosion may be exposed to the direct action of pressure within the pulsating bubble which, although of low peak value, is of long duration.

The radius of the bubble boundary for an unconfined explosion is

$$D_b = 1.5\, W^{1/3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

where the radius D_b is in metres and weight of TNT is in kilograms.

Jacobsen (52) describes a system of using a curtain of air bubbles to reduce shock effects which was used successfully at Niagara. The system was invented and patented by Laprairie of Canadian Industries Ltd.

PROPAGATION IN GROUND

Practical interest in ground propagation is mainly concerned with possible damage to structures by seismic effects when blasting. The matter is considered theoretically and practically in Reference (48).

Damage potential may be related to either the maximum amplitude of ground movement or to the peak particle velocity, the latter being generally accepted as the better criterion. The values of these parameters depend not only on the quantity of explosive and distance but also on the nature of the propagating medium, rock, clay, etc. Thus it is generally necessary to determine the latter by preliminary experiments.

Useful practical data will be found in the handbooks issued by ICI Ltd (50) and Dupont (51).

Much experimental work was sponsored by the Hercules Powder Company and carried out by Rockwell (53) and Leet (54, 55, 56).

The U.S. Bureau of Mines produced a Bulletin on seismic effects by Thoenen and Windes (57).

Edwardes and Northwood (58) described some experimental results on effects on buildings and compared their results with those predicted in (57) and by Crandell (59) and Morris (60).

REACTION WITH STRUCTURES

The behaviour of structures under dynamic loading is beyond the scope of this review. However it is appropriate to consider the response of shock waves to the presence of solid structures. The matter is complex and only the simplest cases can be included.

The simplest cases are the faces of a rectangular structure standing with one face parallel to the approaching plane shock front.

When a shock front meets an unyielding surface head on it is reflected as a positive shock. The properties of the reflected shock may be expressed in terms of its Mach number

$$M_y/M_x = (8M_x^2 + 4)/(M_x^2 + 5) \quad \ldots\ldots\ldots\ldots \quad (12)$$

when, for air $\gamma = 1.4$, and the subscript y refers to the reflected shock.

It is frequently said that the reflected shock is twice the incident shock. This is the limiting condition when $M_x = 1$. The value of M_y/M_x increases to an upper limit of 8 when M_x is very large.

Thus the surface is subjected initially to a pressure indicated by equation (12). The pressure then begins to fall as a rarefaction wave progresses inwards from the edges of the face of the structure.

At the same time pressure on the face is produced by the particles in the shock front being brought to a halt - a pressure known as the stagnation pressure of which the peak value P_s is given by

$$P_s/P_o = (1 + M_x^2/5)^{7/2} \quad . . . . \quad (13)$$

This pressure falls off from its initial value but must be added to the shock pressure.

A graphical method of computing these values is suggested in (1) which also gives tabulated numerical values for reference explosions of one ton of TNT. Graphical representations are given in (27).

The top and sides of the structure which are normal to the incident shock wave are subject to the shock wave side-on pressures during the time the front passes over them.

The rear face experiences no pressure until the shock front reaches the rear edge of the structure. Then a compression wave moves across the rear face. The peak pressure of this wave is the difference P_s-P_d where P_d is the drag pressure due to the blast wind (analogous to the pressure produced by ordinary winds). Drag pressures are dependent on the geometry of the structure as well as the Mach number of the incident shock and may be found conveniently in (1).

As in the case of the other faces the total loading is the integral of the loads on each element of the face.

For shock waves meeting a surface obliquely a graphical method is given by (1). The loading of open frame structures is dealt with by simplified equations in (27).

EFFECTS ON STRUCTURES

For many purposes it is not necessary to calculate the response of a particular structure to a given loading. It suffices to rely on the considerable amount of data from past experience.

Robinson's (28) data is often quoted as giving the damage which may be expected from different quantities of explosive at different distances. Glasstone's (22) compilation of the effects of blast from atomic weapons is also useful.

Jarrett (61) gives an equation used by the U.K.Explosives Storage and Transport Committee to assess the range at which different categories of damage may be expected. A similar classification is given in (27).

For ease of reference I have compiled in Appendix 1 from many sources the best available data on the damage potential of shocks with various peak over-pressures.

BLAST FROM UNCONFINED CLOUDS

The problems of the characteristics of blast from the explosion of a large unconfined cloud have not yet been solved. On the one hand there is very little experimental data or precise information from accidents. On the other hand there are several theories and computer programmes which have been put forward with little data against which they may be checked.

Brasie and Simpson (62) studied the damage done in four accidental industrial explosions. They suggested the use of a TNT equivalent based on the energy content with an efficiency factor for the conversion of the energy into blast. The factor is very variable but a guestimate might be 0.04.

Strehlow (63) compiled a full list of accidental explosions up to 1973 and provides an extensive bibliography. It is apparent however that very few of the explosions were ever investigated in depth and therefore they do not provide much useful data.

Gugan (64) gives Stehlow's list and has expanded it with further discussions on particular cases as also has Davenport (65).

Burgess and Zabetakis (66) investigated the explosion which followed a massive escape of propane in Missouri. They wrongly believed that the cloud detonated.

Reider and others (67) liberated about 1,000 Kg of hydrogen which autoignited. They observed pressure effects.

Fontein (68) and Klopper (69) reported in some detail the fire and explosion at the Shell factory, Pernis, Holland. Goforth (70) and an anonymous writer (71) reported an explosion of isobutylene vapour at Lake Charles, Louisiana.

An explosion at Beek, Holland was reported by the official laboratory TNO (72).

The explosion at Flixborough was fully reported in the official enquiry report (73) and has since been commented on in many publications.

A small amount of experimental work has been reported including that by Kogarko (74), the experiments at China Lake sponsored by the U.S. Coast Guard and reported by Lind (75), and experiments by Tanimoto (76) and Hikita (77).

Theoretical treatments of blast from non-point sources have been given by Kennedy (78) for linear explosions and by Lindberg and Firth (79) for propagation from spherical, linear and plane sources.

Brode (19) considered propagation from an initially static high-pressure sphere. Brinkley (80) considered propagation from a low density source.

Many theoretical treatments stem from Taylor's (81) model of a moving piston, which was the basis for the work by Kuhl and others (82) on the pressures produced by a constant velocity flame.

Strehlow and Adamczyk (83) developed equations as a possible model relating the pressure to time and distance. In a later paper Strehlow and Ricker (84) studied three functionally different formulae, those of Brode (85), Baker (2) and Kinney (1) to obtain an equivalent point source for the explosion of a high pressure sphere. They concluded that Brode's formula was to be preferred.

Houweling (86) developed a generalised shock wave model which he claims is applicable to shock waves from sources over the whole range from nuclear explosions to BLEVES.

Geiger and Synofzik (87) considered blast from a pancake shaped cloud but there must be some doubt about their conclusion that pressures do not extend beyond the area of the cloud.

Other models have been proposed by Munday (88) and Gugan (64).

In a booklet on calculating the effects of escapes of hazardous materials the Dutch TNO (89) suggest methods in respect of vapour cloud explosions.

Although it was mostly concerned with problems of dispersion the Symposium on Heavy Gases at Frankfurt/Main in 1979 included papers on shock effects by Cox and others (90) Giesbucht and others (91) and Geiger and Synofzik (92).

Study of these published theoretical treatments leads to the conclusion that as yet no fully reliable solution to the problem has been found. Inevitably theories are based upon simplifications which may well invalidate them in respect of real clouds. For example it is generally assumed that the vapour concentration is uniform whereas it is almost certainly not. Similarly it is assumed that the cloud is spherical with ignition at the centre. Before these problems can be solved much more information is required on the growth and development of a cloud, its ignition and the mechanism by which pressures are produced.

Some of these problems have recently been theoretically and experimentally studied by Giesbrecht and others (94). They considered the shock wave produced by the rupture of a pressure container of propylene and the expansion of its contents. The characteristics of the cloud produced by flash evaporation and expansion involved a high degree of turbulence and mixing. On ignition it was shown that deflagration occurred in less than 50% of the gas resulting in a pressure field which was studied.

Experiments with cylindrical containers with from 0.12 to 500 kg of propylene gave maximum flame speeds of 50 m/s with peak pressures up to 70 mbar, from the deflagration of about 30% of the released mass.

A large scale check on the theory was obtained by analyses of the damage caused in two rail tank car accidents at BASF in 1943 and 1948 and in the Flixborough accident. It is noteworthy that it is concluded that the peak pressure at the edge of the cloud was about 0.3 bar which is considerably less than the estimates by other authors.

An earlier paper by Baum (95) deals with the first part of Giesbrecht's studies, namely the shock wave generated by the ductile rupture of a pressurised pipe line and expansion of the contents. For a pipe of 152 mm diameter at 46.3 bars the theory gave an estimated peak pressure of 1.8 bars in good agreement with his measured value of 2.2 bars.

In the case of the brittle failure of a pressure vessel the virtually instantaneous rupture may be considered to be analogous to the rupturing of the diaphragm in a shock tube. The resultant shock wave may then be estimated using the data to be found in the several text-books on shock tubes such as that by Wright (96).

CONDENSED CHEMICAL EXPLOSIONS

According to Cook (97) of the ten largest accidental explosions four were due to ammonium nitrate. Other unstable chemicals such as some of the organic peroxides and sodium chlorate have been responsible for accidents. The problem is to find a suitable factor to translate these into a TNT equivalent.

When ammonium nitrate detonates it yields about 40 kcal/mol, that is 500 cal/g which is about one half that of TNT. This is the value under optimum conditions of confinement and initiation. The accidental detonation of a large mass is less efficient. The mass itself will provide some self-confinement but much of the superficial material is likely to be scattered unreacted. Initiation, particularly if it is by slow heating, is also likely to lead to inefficiency. Thus an efficiency of perhaps 50% may be assumed.

Sodium chlorate has been responsible for several accidental explosions, the latest being at Renfrew in 1977 and Barking in 1980. They were reported on by the Health and Safety Executive (98, 99).

The energy of exothermic decomposition is about 150 cal/g, that is one seventh that of TNT. Damage caused in both cases was such that only a small part of the drummed material can have detonated. This was confirmed by experiments carried out jointly by the Home Office and the Ministry of Defence.

Thus in the Barking incident it was estimated that a stock of drums containing about 1700 kg of sodium chlorate gave an explosion comparable to that of 3 - 5 kg. of TNT. This would suggest that only 21 - 35 kg. of the chlorate actually exploded or less than one fiftieth of the total.

Drums of calcium hypochlorite, 70%, with an energy of about 140 cal/g is just about capable of exploding. It explodes more readily if there is a small amount of fuel, such as paper or plastic liners in the drum, present to increase the energy yield.

These examples possibly indicate the two ends of the spectrum of efficiencies. It is tempting to relate efficiency inversely to the specific energy of decomposition with sodium chlorate and calcium hypochlorite near the lower limit below which detonation is theoretically impossible. This may well provide a working guesstimate but account should be taken of all the circumstances, particularly degree of confinement, rate of heating, or strength of initiation, etc. However, since damage at a distance is proportional to the cube root of the weight of explosive, any error in estimating the efficiency will result in a smaller error in the damage estimate.

Thus if a straight line is drawn between a point at 100% efficiency for TNT at 1100 cal/g and another point at zero efficiency at 100 cal/g an approximate efficiency can be read off for any energy output and may be used as a rough guide.

SYMBOLS USED

P_x = Peak overpressure at shock front

P_o = Ambient pressure ahead of shock front

P_s = Stagnation pressure

Pd = Drag pressure

M_x = Mach number of shock, relative to sonic velocity in undisturbed air

M_y = Mach number of reflected shock

M_p = Mach number of particle velocity, relative to sonic velocity in undisturbed air

D = Distance from origin $\bar{D}$ = scaled distance

T = Time from origin $\bar{T}$ = scaled time

I = Impulse $\bar{I}$ = scaled impulse

W = Weight of detonating explosive

E = Energy yield of detonating explosive

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Appendix 1. Peak Pressure/Damage Effects

Pressure psig	Damage
0.02	Annoying noise (137 dB), if of low frequency (10-15 cps)
0.03	Occasional breaking of large glass windows already under strain
0.04	Loud noise (143 dB) Sonic boom glass failure
0.1	Breakage of windows, small, under strain
0.15	Typical pressure for glass failure
0.3	"Safe Distance" (probability 0.05 no serious damage beyond this value)
	Missile limit
	Some damage to house ceilings; > 10% window glass broken
0.4	Limited minor structural damage
0.5 - 1.0	Large and small windows usually shattered; occasional damage to window frames
0.7	Minor damage to house structures
0.75	Breakage of small windows, not under strain
1.0	Partial demolition of houses, made uninhabitable
1 - 2	Corrugated asbestos shattered Corrugated steel or aluminium panels, fastenings fail, followed by buckling Wood panels (standard housing) fastenings fail, panels blown in
1.3	Steel frame of clad building slightly distorted
2	Partial collapse of walls and roofs of houses
2 - 3	Concrete or cinder block walls, not reinforced, shattered
2.3	Lower limit of serious structural damage
2.5	50% destruction of brickwork of house
3	Heavy machines (wt. 3000 lbs) in industrial building suffered little damage

Pressure psig	Damage
3	Frameless, self-framing, steel panel building demolished
	Steel frame building distorted and pulled away from foundations
3 - 4	Frameless, self-framing steel panel building demolished
	Rupture of oil storage tanks
4	Cladding of light industrial buildings ruptured
5	Wooden utilities poles(telegraph etc) snapped
	Tall hydraulic press (40,000 lbs wt) in building slightly damaged
5 - 7	Nearly complete destruction of houses
7	Loaded train wagons overturned
7 - 8	Brick panels, 8 - 12", not reinforced fail by shearing or flexure
9	Loaded train box-cars completely demolished
10	Probable total destruction buildings
	Heavy (7000 lb) machine tools moved and badly damaged
	Very heavy (12000 lb) machine tools survived
283	Limit of crater lip

Damage/distance may be calculated from equation

$$L = C\sqrt[3]{W}$$

L = distance in metres

W = weight TNT in kilograms

C = constant

Values for C and typical distances calculated for 4000 lbs (1900 kg) TNT are

		For 4000lbs TNT		
	C	Metres	Feet	Pressure psi*
Destruction stone and brick buildings	1.5	21	66	>10
Collapse brick walls small houses	3.5	48	150	8
Destruction light partitions	4.5	64	200	5
Damage to wooden doors etc	7	97	300	3
Glass windows broken	10	143	450	1.7
Injury to persons by blast	10	143	450	1.7
Total absence of damage to structures	50-150	700-2100	2300-6800	0.15-0.03

* Taken from Min. Home Security graphs

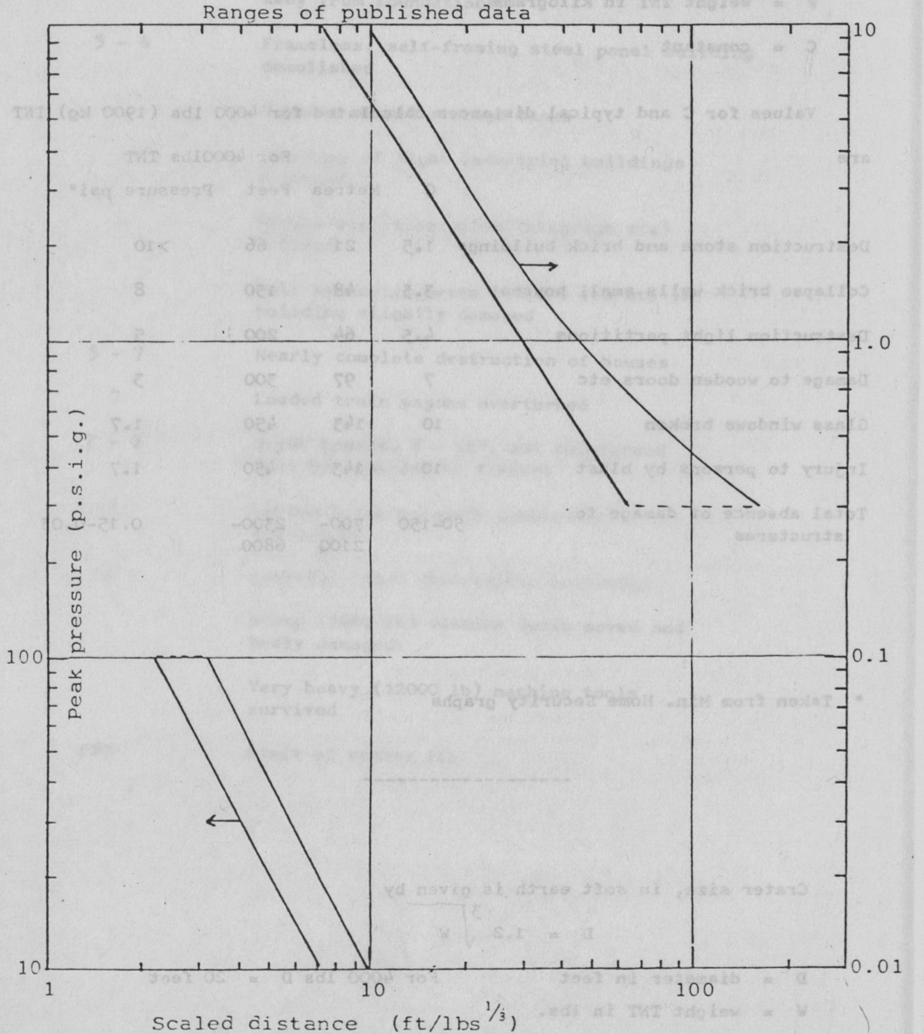
Crater size, in soft earth is given by

$$D = 1.2\sqrt[3]{W}$$

D = diameter in feet For 4000 lbs D = 20 feet

W = weight TNT in lbs.

Appendix 2. Peak side-on over-pressure v. distance for TNT.



(Values unreliable beyond broken lines)

THE THRUST ON THE SUPPORTS OF A TWO CHAMBER VESSEL WHEN THE BURSTING DISC IN THE DUCT CONNECTING THE CHAMBERS IS RUPTURED

W H L PORTER

A method is presented for estimating the maximum thrust on the supports of a reactor vessel connected by way of a duct to a container vessel when the bursting disc in the duct is ruptured. The method is based on an examination of the acceleration of the centre of gravity of the contents of the vessels.

INTRODUCTION

Many hazardous reactions on the chemical industry are performed in autoclave reactor vessels which can be relieved from the effects of overpressure by a bursting disc. Since the contents of the reactor may be toxic or inflammable it is often connected by a duct containing the bursting disc to a container vessel, which accepts the release without allowing it to escape to the environment. When the bursting disc first fails a force will be transmitted to the restraining structure supporting the vessels and it is the purpose of this report to examine the behaviour of the contained gases when rupture of the bursting disc first occurs and the size of the resulting thrust on the structure. The investigation was stimulated by the work of Dr W A Woods and his co-workers. (Ref 4 and 5).

THE BEHAVIOUR OF THE CONTAINED CASES

This paper develops the argument for an ideal gas which can however have an entirely different composition either side of the bursting disc. When the disc first ruptures a shock wave travels downstream towards the container vessel from the bursting disc. This shock wave becomes steeper and sharper as it progresses. At the same time the high pressure end of a rarefaction wave travels upstream towards the reactor vessel, this rarefaction wave becomes ever more extended as it progresses and indeed with higher initial pressure ratios between the two vessels the low pressure end of the rarefaction wave moves in the opposite direction to the high pressure end; in other words, the wave elongates in such a way that its high