

**Design Considerations  
for Toxic Chemical  
and Explosives  
Facilities**

ACS SYMPOSIUM SERIES **345**

# Design Considerations for Toxic Chemical and Explosives Facilities

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## Preface

**T**HIS BOOK DESCRIBES the assessment of the combined hazards of toxic chemical and explosives facilities. The principal considerations regarding explosive and toxic chemical outputs are blast pressure, fragmentation, thermal parameters, and toxic chemical exposures. The book provides design considerations for protecting workers from these outputs and for protecting property within and away from the facilities. Practical examples and protection principles from multiple disciplines are given; these deal with practices, training, site selection, quantity-distance separation, downwind hazard-prediction models, storage methods, and disposal. In addition, methods of measuring and controlling the exposure of workers to toxic chemicals and the development and implementation of engineering and construction features are addressed.

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# Contents

<b>Preface</b> .....	vii
----------------------	-----

## BLAST PRESSURE AND FRAGMENTATION EFFECTS

1. <b>Blast Pressure Effects: An Overview</b> .....	2
W. E. Baker	
2. <b>Fragmentation Effects: An Overview</b> .....	58
Michael M. Swisdak, Jr., and Joseph G. Powell, Jr.	
3. <b>Architectural Standard Details for Army Ammunition Plants</b> .....	68
Richard W. Sime	
4. <b>Explosives Storage Structures</b> .....	85
Richard L. Wight	
5. <b>Reinforced Concrete in Blast-Hardened Structures</b> .....	92
James E. Tancreto	
6. <b>Blast-Resistant Glazing</b> .....	107
Gerald E. Meyers	
7. <b>Interim Design Criteria for Polycarbonate Blast-Resistant Glazing</b> .....	130
Gerald E. Meyers and James E. Tancreto	

## THERMAL EFFECTS

8. <b>Thermal Effects: An Overview</b> .....	148
W. R. Herrera and L. M. Vargas	
9. <b>Remote Mixing and Handling Procedures for Pyrotechnic Materials</b> .....	152
Thomas E. Shook, Loy M. Aikman, Max Frauenthal, David Garcia, Joe G. Janski, and F. L. McIntyre	
10. <b>Engineering Design for White Phosphorus Filling Operations and Facilities</b> .....	168
Harold D. McKinney	
11. <b>Design and Use of High-Speed Detection Systems for Explosives Operations</b> .....	183
Kenneth M. Klapmeier and Bernhard G. Stinger	
12. <b>Ultra-High-Speed Fire Suppression for Explosives Facilities</b> .....	200
Gary A. Fadorsen	

## CHEMICAL EFFECTS

13. <b>Systematic Approach for Safely Designing a Chemical Surety Materiel Laboratory</b> .....	212
George E. Collins, Jr.	



14. Laboratory Design.....	224
Frances H. Cohen	
15. Design Considerations for Toxic Laboratories.....	234
William J. Maurits	
16. Design of Blast-Containment Rooms for Toxic Chemical Ammunition Disposal.....	241
Paul M. LaHoud	

#### OTHER DESIGN CONSIDERATIONS

17. Intrinsically Safe Electrical Circuits in Explosives Facilities.....	254
Kenneth W. Proper	
18. Electrostatic Studies in Army Ammunition Plants.....	269
William O. Seals, James Hokenson, and George Petino	
19. Ionizing Air for Static Charge Neutralization While Processing Sensitive Materials.....	286
B. V. Diercks	
20. Design and Use of Ammunition Peculiar Equipment To Protect Workers.....	294
Mark M. Zaugg	
21. Cleaning Process Lines in the Explosives Industry.....	300
Roy W. Wheeler	

#### INDEXES

Author Index.....	306
Affiliation Index.....	306
Subject Index.....	306

## BLAST PRESSURE AND FRAGMENTATION EFFECTS

## Chapter 1

# Blast Pressure Effects: An Overview

W. E. Baker

Wilfred Baker, Inc., P.O. Box 6477, San Antonio, TX 78209

This keynote paper gives a general discussion of blast waves developed by high explosive detonations, their effects on structures and people, and risk assessment methods. The properties of free-field waves and normally and obliquely reflected waves are reviewed. Diffraction around block shapes and slender obstacles is covered next. Blast and gas pressures from explosions within vented structures are summarized.

Simplified methods of estimating damage to structures by blast waves appear next, followed by methods of estimating blast spalling for strong blasts.

Prediction curves or graphs are given for external blast wave properties, and internal blast and gas transient pressures.

Practical techniques for explosion containment and venting are discussed, and the topic of risk assessment for explosives facilities is reviewed.

A selected reference list closes the paper.

### Blast Pressures

Basics of Free-Field Blast Waves. The most severe types of energy releases which can occur in toxic chemical and explosives facilities are explosions of high explosive materials. When such materials are initiated by some stimulus, they may burn, deflagrate or detonate. Detonation is by far the most severe of these three chemical reactions, so it is usually assumed to occur in accident situations, unless one can prove otherwise quite conclusively.

A detonation wave is a very rapid wave of chemical reaction which, once it is initiated, travels at a stable supersonic speed, called the detonation velocity, in a high explosive. Typically, detonation velocities for pressed or cast high explosives range from

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22,000 - 28,000 ft/sec. As the detonation wave progresses through the condensed explosive, it converts the explosive within a fraction of a microsecond into very hot, dense, high pressure gas. Pressures immediately behind the detonation front range from 2,700,000 - 4,900,000 psi. (These pressures are called Chapman-Jouquet, or CJ, pressures.)

The most important single parameter for determining air blast wave characteristics of high explosives is the total heat of detonation,  $E$ . This quantity is, in general, directly proportional to the total weight  $W$  or mass  $M$  of the explosive. Any given explosive has a specific heat of detonation,  $\Delta H_e$  per unit weight or mass, which can be either calculated from chemical reaction formulas or measured calorimetrically (see References 1-3). So  $E$  equals  $W \cdot \Delta H_e$  or  $M \cdot \Delta H_e$ , depending on units for  $\Delta H_e$ . Values for  $\Delta H_e$  for many explosives are given in References 1 and 4.

If the detonating explosive is bare, the detonation wave propagates out into the surrounding air as an intense shock or blast wave, and is driven by the expanding hot gases which had been the explosive material. If it is encased, the detonation wave simply overpowers the casing material, and drives it outward at high velocity until the casing fragments. The high pressure gases then vent out past the casing fragments and again drive a strong blast wave into the surrounding atmosphere.

As the blast wave expands, it decays in strength, lengthens in duration, and slows down, both because of spherical divergence and because the chemical reaction is over, except for afterburning as the hot explosion products mix with the surrounding air.

Good descriptions of the characteristics of air blast waves appear in References 5-7. The description here is paraphrased from Reference 5.

As a blast wave passes through the air or interacts with and loads a structure or target, rapid variations in pressure, density, temperature and particle velocity occur. The properties of blast waves which are usually defined are related both to the properties which can be easily measured or observed and to properties which can be correlated with blast damage patterns. It is relatively easy to measure shock front arrival times and velocities and entire time histories of overpressures. Measurement of density variations and time histories of particle velocity are more difficult, and few reliable measurements of temperature variations exist.

Classically, the properties which are usually defined and measured are those of the undisturbed or side-on wave as it propagates through the air. Figure 1 shows graphically some of these properties in an ideal wave. Prior to shock front arrival, the pressure is ambient pressure  $p_0$ . At arrival time  $t_a$ , the pressure rises quite abruptly (discontinuously, in an ideal wave) to a peak value  $P_s + p_0$ . The pressure then decays to ambient in total time  $t_a + t_d$ , drops to a partial vacuum and eventually returns to  $p_0$ . The quantity  $P_s$  is usually termed the peak side-on overpressure, or merely the peak overpressure. The portion of the time history above initial ambient pressure is called the positive phase, of duration  $t_d$ . That portion below  $p_0$  is called the negative phase. Positive specific impulse, defined by



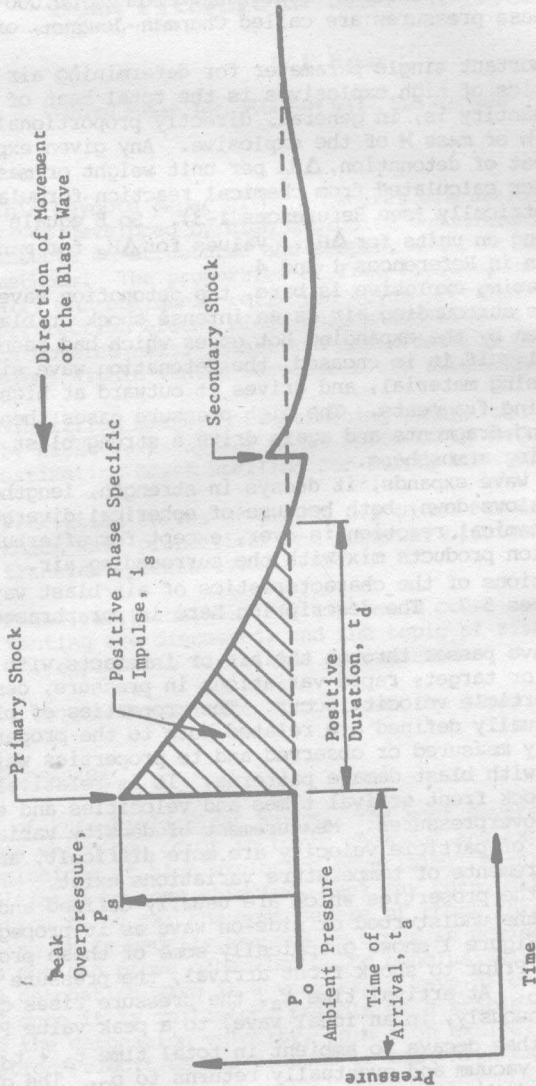


Figure 1. Idealized Profile of a Blast Wave from a Condensed High Explosive. (Courtesy Oyez Scientific and Technical Services Ltd.)

$$i_s = \int_{t_a}^{t_a + t_d} [p(t) - p_0] dt \quad (1)$$

is also a significant blast wave parameter. This impulse is shown by the cross-hatched area in Figure 1. (The units of  $i$  are force times time divided by length squared, or pressure times time. They are, therefore specific impulse or impulse per unit area, rather than true impulse, which has units of force times time.)

In most blast studies, the negative phase of the blast wave does not affect damage and is ignored, and only blast parameters associated with the positive phase are considered or reported. The ideal side-on parameters almost never represent the actual pressure loading applied to structures or targets following an explosion. So a number of other properties are defined to either more closely approximate real blast loads or to provide upper limits for such loads. (The processes of reflection and diffraction will be discussed later.) Properties of free-field blast waves other than side-on pressure which can be important in structural loading are:

Density,  $\rho$   
 Particle velocity,  $u$   
 Shock front velocity,  $U$   
 Dynamic pressure  $q = \rho u^2/2$

Because of the importance of the dynamic pressure  $q$  in drag or wind effects and target tumbling, it is often reported as a blast wave property. In some instances drag specific impulse  $i_d$ , defined as

$$i_d = \int_{t_a}^{t_a + t_d} q \, dt = \frac{1}{2} \int_{t_a}^{t_a + t_d} \rho u^2 \, dt \quad (2)$$

is also reported.

Although it is possible to define the potential or kinetic energy in blast waves, it is not customary in air blast technology to report or compute these properties. For underwater explosions, the use of "energy flux density" is more common. This quantity is given approximately by

$$E_f = \frac{1}{\rho_0 a_0} \int_{t_a}^{t_a + t_d} [p(t) - p_0]^2 \, dt \quad (3)$$

where  $\rho_0$  and  $a_0$  are density and sound velocity in water ahead of the shock.

At the shock front in free air, a number of wave properties are interrelated through the Rankine-Hugoniot equations. These three equations are (Reference 5):

$$\rho_S(u_S - U) = \rho_O(u_O - U) \quad (4)$$

$$\rho_S(u_S - U)^2 + p_S = \rho_O(u_O - U)^2 + p_O \quad (5)$$

$$\left(\frac{1}{2} u_O^2 + e_O\right) (u_O - U) + p_O u_O = \left(\frac{1}{2} u_S^2 + e_S\right) (u_S - U) + p_S u_S \quad (6)$$

In these equations, subscript s refers to peak quantities immediately behind the ideal shock front, e is internal energy, and

$$p_S = p_S + p_O \quad (7)$$

Scaling of the properties of blast waves from explosive sources is a common practice, and anyone who has even a rudimentary knowledge of blast technology utilizes these laws to predict the properties of blast waves from large-scale explosions based on tests on a much smaller scale. Similarly, results of tests conducted at sea level ambient atmospheric conditions are routinely used to predict the properties of blast waves from explosions detonated under high altitude conditions.

The most common form of blast scaling is Hopkinson-Cranz or "cube-root" scaling. This law, first formulated by B. Hopkinson (Reference 8) and independently by C. Cranz (Reference 9), states that self-similar blast waves are produced at identical scaled distances when two explosive charges of similar geometry and of the same explosive, but of different sizes, are detonated in the same atmosphere. It is customary to use as a scaled distance a dimensional parameter,

$$Z = R/E^{1/3} \quad (8)$$

or

$$Z = R/W^{1/3} \quad (9)$$

where R is the distance from the center of the explosive source, E is the total heat of detonation of the explosive and W is the total weight of a standard explosive such as TNT. The correct equation, Equation 8 or 9, will be apparent in the problem. Figure 2 shows schematically the implications of Hopkinson-Cranz blast wave scaling. An observer located at a distance R from the

center of an explosive source of characteristic dimension  $d$  will be subjected to a blast wave with amplitude  $P$ , duration  $t_d$ , and a characteristic time history. The integral of the pressure-time history is the impulse  $i$ . The Hopkinson-Cranz scaling law then states that an observer stationed at a distance  $\lambda R$  from the center of a similar explosive source of characteristic dimension  $\lambda d$  detonated in the same atmosphere will feel a blast wave of "similar" form with amplitude  $P$ , duration  $\lambda t_d$  and impulse  $\lambda i$ . All characteristic times are scaled by the same factor as the length scale factor  $\lambda$ . In Hopkinson-Cranz scaling, pressures, temperatures, densities and velocities are unchanged at homologous times. This scaling law has been thoroughly verified by many experiments conducted over a large range of explosive charge energies. A much more complete discussion of this law and demonstration of its applicability is given in Chapter 3 of Reference 5.

The blast scaling law which is almost universally used to predict characteristics of blast waves from explosions at high altitude is that of Sachs (Reference 10). Sachs' law states that dimensionless overpressure and dimensionless impulse can be expressed as unique functions of a dimensionless scaled distance, where the dimensionless parameters include quantities which define the ambient atmospheric conditions prior to the explosion. Sachs' scaled pressure is

$$\bar{P} = (P/p_0) \quad (10)$$

Sachs' scaled impulse is defined as

$$\bar{i} = \frac{ia_0}{E^{1/3} p_0^{2/3}} \quad (11)$$

where  $a_0$  is ambient sound velocity. These quantities are a function of dimensionless scaled distance, defined as

$$\bar{R} = R \left( \frac{p_0}{E} \right)^{1/3} \quad (12)$$

Both scaling laws apply to reflected blast wave parameters, as well as side-on parameters. (Note that, if charge weight  $W$  is used instead of energy  $E$ , these parameters have dimensions.)



### Basics of Reflection and Diffraction Processes

**Normal Reflection.** An upper limit to blast loads is obtained if one interposes an infinite, rigid wall in front of the wave, and reflects the wave normally. All flow behind the wave is stopped, and pressures are considerably greater than side-on. The pressure in normally reflected waves is usually designated  $p_r(t)$ , and the peak reflected overpressure,  $P_r$ . The integral of overpressure over the positive phase, defined in Equation (13), is the reflected specific impulse  $i_r$ . Durations of the positive phase of normally reflected waves are almost the same as for side-on waves,  $t_d$ . The parameter  $i_r$  has been measured closer to high explosive blast sources than have most blast parameters.

$$i_r = \int_{t_a}^{t_a + t_d} [p_r(t) - p_0] dt \quad (13)$$

The Hopkinson-Cranz scaling law described earlier applies to scaling of reflected blast wave parameters just as well as it does to side-on waves. That is, all reflected blast data taken under the same atmospheric conditions for the same type of explosive source can be reduced to a common base for comparison and prediction. Sachs' law for reflected waves fails close to high explosive blast sources but it does apply beyond about ten charge radii.

For shock waves weak enough that air behaves as a perfect gas, there is a fixed and well-known relation between peak reflected overpressure and peak side-on overpressure (References 5 and 11).

$$\bar{P}_r = 2 \bar{P}_s + \frac{(\gamma+1) \bar{P}_s^2}{(\gamma-1) \bar{P}_s + 2} \quad (14)$$

$$\bar{P}_s = P_s/p_0 \quad (15)$$

$$\bar{P}_r = P_r/p_0 \quad (16)$$

At low incident overpressures ( $P_s \rightarrow 0$ ), the reflected overpressure approaches the acoustic limit of twice the incident overpressure. If one were to assume a constant  $\gamma = 1.4$  for air for strong shocks, the upper limit would appear to be  $P_r = 8P_s$ . But, air ionizes and dissociates as shock strengths increase, and  $\gamma$  is not constant. In fact, the real upper limit ratio is not exactly known, but is predicted by Doering and Burkhardt (Reference 11) to be as high as 20. Brode (Reference 12) has also calculated this ratio for normal reflection of shocks in sea level air, assuming air dissociation and ionization.