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Quick Reference Guide for Terms Used in Air Blast Research and Experimentation

by Steven J Trombetta

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Quick Reference Guide for Terms Used in Air Blast Research and Experimentation

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14. ABSTRACT

This report provides an overview of common terms used in the technical areas of air blast research and experimentation. The descriptions provided are based on extensive experience researching blast in military applications, with a focus on air blast from both fragmenting and non-fragmenting munitions in unconfined conditions (free air, surface burst, or near-surface burst).

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1. Introduction

While studying or conducting research in a specific technical area, it is useful to have easy access to the important or frequently used definitions in that area. Many manuals and reports detailing air blast research and experimentation exist. However, definitions of the most frequently used terms are scattered about several sources that are often hundreds of pages long. Additionally, many terms used are unique to the air blast community and thus some of these terms may be confusing to someone new to the technical area of air blast.

The intent of this report is to provide clearly defined terms that are useful for air blast research and experimentation with background information, where appropriate, for a better understanding of terms and concepts. The reader may find more in-depth coverage of a term or topic by following the source from which it was cited. This report documents some of the common terms used by the Explosive Effects Branch (EEB), a branch formed in the 1990s within the Weapons and Materials Research Directorate of the US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL). One of the primary focuses of EEB is the characterization and performance of explosive formulations and munitions, and therefore the branch has members with unique expertise in air blast phenomenology.

This report predominantly focuses on air blast from explosive weapons for military applications in unconfined spaces. As such, most terms are related to their use with characterizing the blast from an explosive chemical energy weapon in free air, on the ground surface (a surface burst), or near the ground surface (a near-surface burst). However, many definitions may be expanded and applied to any type of event that creates a pressure wave of finite amplitude in the air. On this note, readers should be aware that different authors may use different terms or definitions than those presented here. The terms and definitions within a particular report should be understood prior to referencing that report and not assumed to match the definitions given here; however, in this report terms were defined based on their common or typical usage within the air blast community.

2. Terminology

Terms are grouped into sections one naturally considers while researching air blast or planning experiments, starting with detonation, explosion, and energy; and then progressing through to distance, pressure, pressure measurement, and fragmentation. The last section with terminology discusses scaling laws and computer programs. These are important tools in air blast research and experimentation.

The definition of each term is presented here either verbatim or slightly paraphrased from the cited source. Where terms are synonyms, the definition is placed with the most commonly used term. The synonymous term(s) will direct the reader to see this definition (e.g., Ground Distance: see Range). Terms are listed in alphabetical order within each section and may include additional information after the technical definition or an illustrative figure for clarity. Figure 1 in Section 2.2 and Fig. 2 in Section 2.3 illustrate multiple terms from those sections.

2.1 Detonation, Explosion, and Energy

Air Blast: A process by which a pressure wave of finite amplitude is generated in air by a rapid release of energy (Army Materiel Command 1974, p. 1-2, modified).

Chemical Energy: Energy stored in the bonds of chemical compounds. Chemical energy may be released during a chemical reaction, often in the form of heat (Encyclopaedia Britannica n.d.).

Deflagration: A rapid chemical reaction in which the output of heat is enough to enable the reaction to proceed and be accelerated without input of heat from another source. Deflagration is a surface phenomenon with the reaction products flowing away from the unreacted material along the surface at subsonic velocity. The effect of a true deflagration under confinement is an explosion. Confinement of the reaction increases pressure, rate of reaction and temperature, and may cause transition into a detonation (Under Secretary of Defense for Acquisition and Technology 1999, p. 234).

A less formal description per the Under Secretary of Defense for Acquisition and Technology is "an exothermic reaction that propagates from the burning gases to the unreacted material by conduction, convection, and radiation. In this process, the combustion zone progresses through the material at a rate that is less than the velocity of sound in the unreacted material" (1999, p. 31).

Detonation: An exothermic reaction that is characterized by the presence of a shock wave in the material that establishes and maintains the reaction. A distinctive difference from deflagration is that the reaction zone during detonation propagates at a rate greater than sound velocity in the unreacted material. Every material capable of detonating has a characteristic velocity that is under fixed conditions of composition, temperature, and density (Under Secretary of Defense for Acquisition and Technology 1999, p. 31).

Burns describes detonation as “a violent chemical reaction within a compound or mixture that is initiated by heat accompanying a shock. This is a subsurface reaction where chemical energy is released before expansion occurs to sustain the shock wave. This reaction is supersonic (2000–9000 m/s) and evolves tremendous amounts of pressure and heat” (Burns 2008, p. 335).

Explosion: A chemical reaction of any chemical compound or mechanical mixture that, when initiated, undergoes a very rapid combustion or decomposition releasing large volumes of highly heated gases that exert pressure on the surrounding medium. Also, a mechanical reaction in which failure of the container causes the sudden release of pressure from within a pressure vessel, for example, pressure rupture of a steam boiler. Depending on the rate of energy release, an explosion can be categorized as a deflagration, a detonation, or pressure rupture (Under Secretary of Defense for Acquisition and Technology 1999, p. 236).

Explosive: A substance or a mixture of substances that is capable by chemical reaction of producing gas at such temperature, pressure, and speed as to cause damage to the surroundings. The term “explosive” includes all substances variously known as high explosives and propellants, together with igniters, primers, initiators, and pyrotechnics (e.g., illuminant, smoke, delay, decoy, flare, and incendiary compositions) (Office of the Deputy Under Secretary of Defense 2008, p. 301).

Heat of Detonation: Heat liberated at calorimeter temperature when an explosive detonates at constant volume and with no change in the product composition from that which was obtained at the C-J point (Fedoroff and Sheffield 1969, p. D375).

Heat of detonation may be used as the specific energy of the explosives in certain scaling techniques (e.g., TNT equivalency). The heat of detonation can be measured easily for chemical explosives in the laboratory by detonating small quantities of the explosive in a bomb calorimeter that has been purged and pressurized with an inert gas (Army Materiel Command 1974, p. 3-3).

The total heat of detonation is considered the single most important parameter for determining air blast wave characteristics of high explosives. This quantity is, in general, directly proportional to the weight or mass of the explosive (Department of Energy 1992, p. 4-6).

The heat of detonation is, like the heat of explosion, a function of the chemical energy of the explosive. In fact, the two heats differ only by the thermal effect, at standard temperature, of the shift in composition of the product mixture between the C-J temperature and the temperature of detonation. This depends on the elementary balance, particularly that of oxygen (Fedoroff and Sheffield 1969, pp. D375 to D376).

See Table 2-1 in TM 5-1300 for a list of the heat of detonation for some of the more commonly used explosives (Departments of the Army, the Navy, and the Air Force 1990, p. 2-278).

Heat of Explosion: Heat liberated at calorimeter temperature when an explosive explodes at constant volume (Fedoroff and Sheffield 1969, p. D375).

Kinetic Energy: Energy associated with motion (Merriam-Webster n.d.).

Thermal Energy: Energy in the form of heat (Merriam-Webster n.d.).

2.2 Distance or Location

Ground Distance: see Range.

Ground Range: see Range.

Ground Zero (GZ): (1) The point on the ground surface closest to the center of mass of the explosives in an explosive weapon. (2) The normal projection of the center of mass of the explosives in an explosive weapon to the ground plane.

See Fig. 1 for an illustration of this term.

Height of Burst: The distance between the center of mass of the explosives in an explosive weapon and the ground directly beneath.

The height of burst is important for determining the effects of ground reflections and for trigonometry of determining the standoff (if not measured directly).

See Fig. 1 for an illustration of this term.

Range: (1) The shortest distance parallel to the ground plane between ground zero and a location on the target. (2) The horizontal distance between a weapon and target (Merriam-Webster n.d.).

May also be referred to as ground range or ground distance to prevent ambiguity. The measurement is typically taken to the center of mass of the explosives in an explosive weapon.

See Fig. 1 for an illustration of this term.

Slant Distance: see Slant Range

Slant Range: The shortest distance between a weapon and a location on the target.

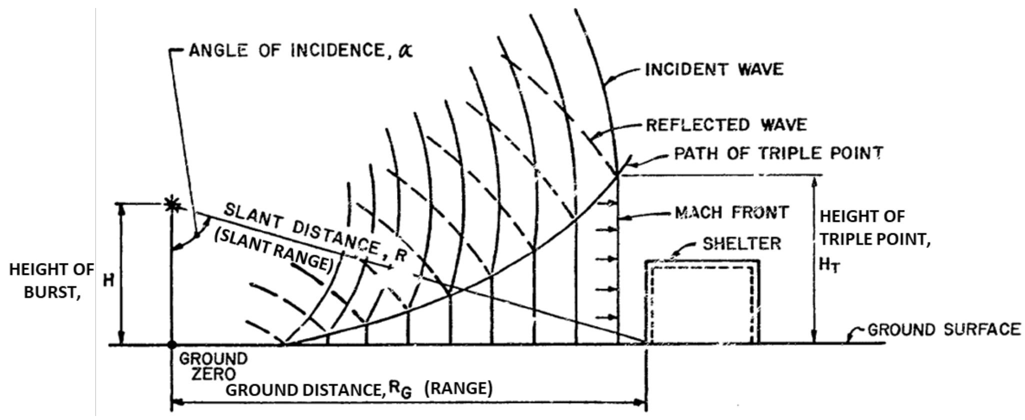
The measurement is typically taken to the center of mass of the explosives in an explosive weapon.

See Fig. 1 for an illustration of this term.

Standoff: see Slant Range.

Standoff Distance: see Slant Range.

Several distance terms are illustrated in Fig. 1 along with some useful information detailing pressure wave propagation near the ground (terms discussed in next section).



Slant range (R) and range (R_G) may be measured to any point of interest on the target, shown here as the point where the target meets the ground nearest the threat.

Fig. 1 Illustration of distance terms and blast interaction with the ground (Departments of the Army, Navy, and Air Force 1990, Fig. 2-11, modified)

2.3 Pressure, Impulse, and Velocity of an Explosion

Dynamic Pressure: The force per unit area caused by the gross motion of the gas. Usually defined as one-half the density times the square of the velocity of the gas (Needham 2010, p. 3).

$$q = \frac{1}{2}\rho * |u|^2 \tag{1}$$

where q is the dynamic pressure, ρ is the density of the gas behind the shock front, and u is the velocity of the gas (also known as the particle velocity). While Needham's definition makes no mention of a surface, it is understood that pressure is a surface force (and not a body force).

Per the Department of Energy, "Dynamic pressures are formed by the winds produced by the passage of the shock front…" (1992, p. 4-19). "Dynamic pressure is often reported as a blast wave property because of its importance in drag or wind effects, and in target tumbling" (1992, p. 4-8).

“[Dynamic pressure is the] kinetic energy per unit volume of air immediately behind the shock front” (Department of Energy 1992, p. 4-19). Although it represents the kinetic energy component of a gas particle, dynamic pressure is usually expressed in typical pressure units of force per area, such as pascals (N/m^2) or psi (lbf/in^2).

Equation 1, the fundamental equation for dynamic pressure, is rarely used in practice because measurement of the gas density and particle velocity is difficult in a blast environment. Dynamic pressure is typically determined in blast environments by measuring the total and side-on pressures, and then subtracting the side-on pressure from the total pressure. The associated setup and equation are provided in the “Air Blast” illustration on the left in Fig. 2. The figure also includes a correlation to classical fluid dynamic terms to help in comprehension.

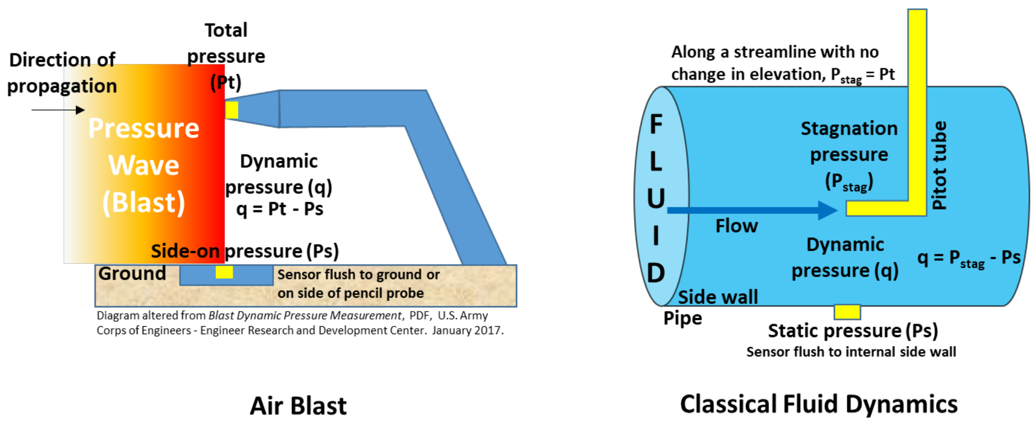


Fig. 2 Relation of total, dynamic, and side-on pressures to classical fluid dynamic terms

The maximum dynamic pressure may be estimated in the absence of a total pressure measurement by using the peak side-on overpressure and an assumption of the ratio of specific heats, γ (also called the heat capacity ratio). When γ = 1.4, which is typical of most air blast situations, the following equation may be used (Department of Energy 1992, eq. 4.21):

$$q = \frac{5}{2}\left(\frac{{P_S}^2}{7P_0+P_S}\right) \qquad (2)$$

where q is the dynamic pressure, P_s is the peak side-on overpressure, and P_0 is the ambient atmospheric pressure. Refer to DOE/TIC-11268 (Department of Energy 1992) for additional information on proper usage of this equation.

Impulse: see Specific Impulse.

Incident Impulse: see Side-on Impulse.

Incident Pressure: see Side-on Pressure.

The use of "side-on" over "incident" is preferred to reduce confusion with the incident wave, which may be measured for dynamic, stagnation, or incident (side-on) pressures.

Overpressure: (1) Pressure in excess of the initial ambient pressure. (2) The difference in pressure from the initial ambient pressure.

This term is sometimes used interchangeably with side-on pressure, which can cause confusion. EEB tries to delineate pressure terms since overpressure can be used to describe any pressure measurement that is higher than ambient conditions (e.g., side-on, dynamic, and total pressures may all have "overpressure" values).

Also known as gauge pressure.

Mach Front: A shock wave formed by the fusion of [the] incident and reflected shock waves from an explosion (Wikipedia n.d., Mach Stem).

Also referred to as Mach shock, Mach stem, or Mach shock front. See Fig. 3 for an illustration of the Mach front formed from the near-surface burst of a spherical charge.

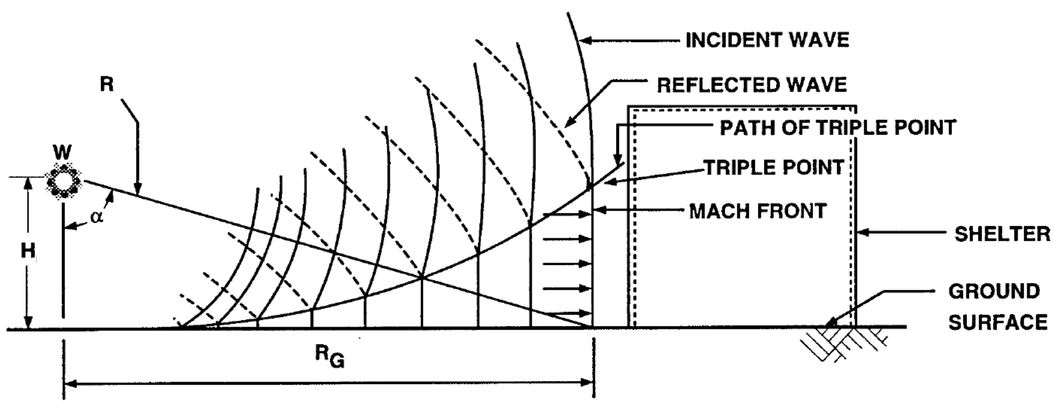


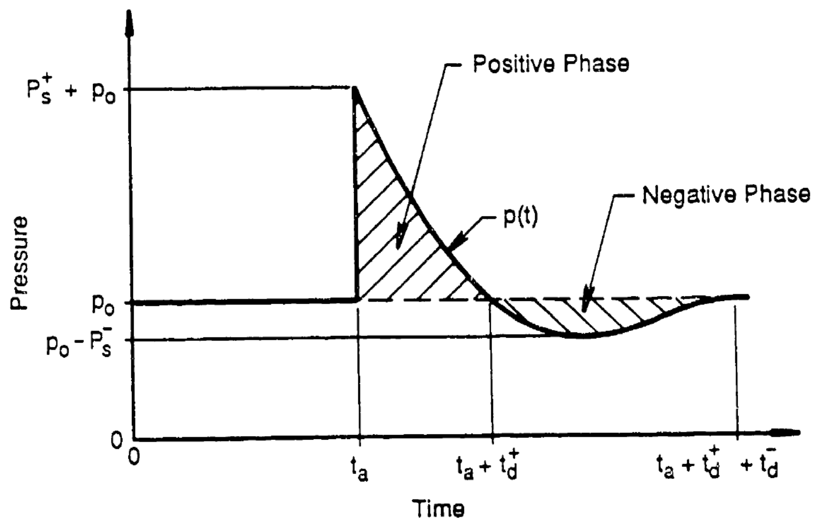
Fig. 3 Mach front from a near-surface burst (Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency 1997, Fig. 5-10)

A common formation of the Mach front in air blast is near the ground where the incident and ground reflected shocks merge, as shown in Fig. 3 and similarly in Fig. 1. The last paragraph in the definition of Reflected Pressure also provides a written description of the Mach front formation for a blast source detonated near a reflecting surface (such as the ground). The formation of Mach stem is further described in the sources provided in Section 3, with pp. 1-9 to 1-12 in AMC Pamphlet 706-181 providing a nice introduction (Army Material Command 1974).

Mach Shock: see Mach Front.

Mach Stem: see Mach Front.

Negative Phase: (1) The portion of the pressure-time history below (less than) the initial ambient pressure. (2) The period of time where the pressure is a value lower than the ambient pressure. See Fig. 4 for an illustration.



Note: Initial ambient pressure (prior to blast) is p_0.

Fig. 4 Positive and negative phases of an ideal blast wave (Department of Energy 1992, Fig. 4.1)

Particle Velocity: The velocity of the air particles (gas molecules) as they transmit the pressure wave from a blast.

Sometimes called flow velocity, the particle velocity is an important parameter in several fundamental equations encountered in air blast. The particle velocity is slower than the shock front velocity and is associated with the dynamic pressure (Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency 1997, pp. 5-1 to 5-2).

Positive Phase: (1) The portion of the pressure-time history above (in excess of) the initial ambient pressure. (Army Materiel Command 1974, p. 1-3). (2) The period of time where the pressure is a value higher than the ambient pressure. See Fig. 4 for an illustration.

Pressure: The force per unit area caused by the molecular or atomic linear motion of the gas. Pressure may also be expressed in terms of energy per unit volume (Needham 2010, p. 4, modified).

The pressure term defined here is specific towards gas pressure, since in air blast we are primarily concerned with the pressure imposed by the compressed air and detonation products (mostly gases) from the explosion. At its root, pressure is the normal force per unit area over which that force is distributed (Wikipedia n.d., Pressure). Common units are pascals (N/m^2) or psi (lbf/in^2). When relating pressure to energy, pressure may be expressed as joules per cubic meter (J/m^3).

Rarefaction Wave: A wave of lower pressure and density than its immediate environment that reduces blast overpressure and usually propagates in the reflected pressure region.

Zhang describes a Rarefaction Wave as "the progression of particles being accelerated away from a compressed or shocked zone. It travels in the direction opposite to the acceleration of the particles. This is opposite to a shock wave, where the particles are accelerated in the direction of the shock" (2016, p. 61).

At the instant the reflected shock front is formed, the lower pressure existing in the incident blast wave and adjacent to the edges of the impinged surface initiate a wave of lower pressure than that which exists in the reflected shock wave. This wave of low relative pressure is known as the rarefaction wave (Yasseri et al. 2002, p. 6.3).

A rarefaction wave propagates from the low to the high pressure region and travels at the velocity of sound in the reflected pressure region. Rarefaction waves reduce the reflected pressures to the stagnation pressure (Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency 1997, p. 5-4).

Per Zhang, "Unlike a shock wave, which is nearly a discontinuity and is very steady, a rarefaction wave is spread out in space, and continues to spread out with time. This is because the expansion of the high-density material to a lower density takes time. In other words, the velocity of a rarefaction wave is dependent on time" (2016, p. 61).

Reflected Impulse: The integral of reflected pressure over the time interval for which it acts.

Reflected Pressure: (1) The pressure that is reflected from a surface oriented at an angle to the direction of propagation of the shock wave (Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency 1997, p. 5-2, modified); (2) The pressure caused by the reflection of a shock wave from a non-responding surface (Needham 2010, p. 4).

As pressure is stopped by a rigid (non-responding) surface, it reflects, causing a pressure higher than the side-on pressure. The magnitude of this reflected pressure is a function of the magnitude of the side-on pressure and the obliquity of the surface (angle of incidence). The duration of the reflected pressure wave is the same or less than the duration of the side-on pressure wave and is primarily effected by the size of the reflecting surface. If the surface is infinite, the duration will be the same as the side-on pressure duration. Otherwise, the reflected pressure is relieved by the rarefaction waves that form at the edges of the structure (and travel into the reflected region) and the duration is less than that of the side-on pressure. (paraphrased and modified from Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency 1997, p. 5-2 and 5-4; Yasseri et al. 2002, p. 6.5).

Reflected pressure is measured by mounting a flush diaphragm pressure transducer in, or through, an object so the sensing element (diaphragm) is flush to the reflecting surface. Reflected pressure is expressed in typical pressure units of force per area, such as pascals (N/m^2) or psi (lbf/in^2). Reflected pressure in air blast is synonymous to the usage in classical fluid dynamics, as demonstrated in Fig. 5.

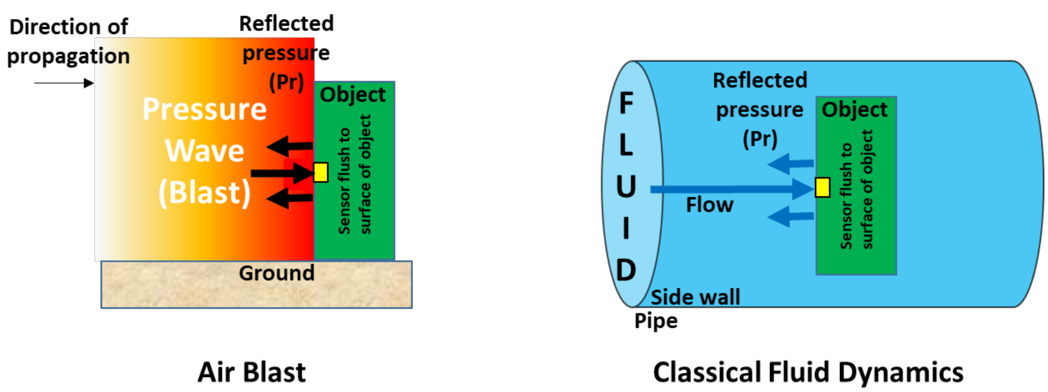


Fig. 5 Reflected pressure (shown in air blast and classical fluid dynamic cases)

In the absence of a direct measurement, the peak reflected pressure is obtained by multiplying the peak side-on pressure by a reflected pressure coefficient. The reflected pressure coefficients for angles of incidence ranging from 0° to 90° and peak side-on pressures ranging from 1.4E-3 to 34.17 MPa may be found in Fig. 5-3 of TM 5-855-1 (Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency 1997, p. 5-2). Reflected pressure is a maximum when the incident shock velocity is perpendicular to the reflecting surface, but is not a monotonic function of the incident angle (Needham 2010, p. 4).

The reflected pressure from the detonation of a bare sphere of explosive may be approximated for a normal reflecting surface (perpendicular to shock front velocity) by using the peak incident overpressure and an assumption of the ratio of specific heats, γ (also called the heat capacity ratio). When γ = 1.4, which is typical of most air blast situations, and the ratio of reflected pressure to initial ambient pressure is less than 3.5 (indicating a moderate to weak shock strength), then Eq. 3 may be used to determine reflected pressure (Needham 2010, eq. 3.14):

$$P_r = 2P_s\left(\frac{7+4P_s/P_0}{7+P_s/P_0}\right) \quad (3)$$

where P_r is the reflected overpressure, P_s is the peak side-on overpressure, and P_0 is the ambient atmospheric pressure. Refer to *Blast Waves* (Needham 2010, p. 14) for additional information on proper usage of this equation. AMC Pamphlet 706-181 (Army Materiel Command 1974, p. 6-7) and DOE/TIC-11268 (Department of Energy 1992, p. 4-24) contain additional information for equations of similar form.

As described in AMC Pamphlet 706-181, "If a blast source is placed on or near a reflecting surface such as the ground, then the initial shock is very quickly reflected, and the reflected wave merges with the incident wave so rapidly that a single, strengthened blast wave is formed" (Army Materiel Command 1974, pp. 5-5 to 5-6). The incident pressure of this strengthened blast wave (Mach stem) may be estimated by multiplying the free air incident pressure by a reflection pressure coefficient. A coefficient of 1.8 provides reasonable predictions of surface burst parameters from free air values for a hemispherical charge placed on a ground of typical compacted soil (Department of Energy 1992, p. 4-35). A coefficient of 2 may be used if the hemispherical charge is placed on a perfect (or near perfect) reflecting surface, such as a thick, non-responding steel plate.

Release Wave: see Rarefaction Wave.

Relief Wave: See Rarefaction Wave.

Shock Front: The abrupt, almost instantaneous, increase in pressure generated in a medium during an explosion (Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency 1997, pp. 5-1 to 5-2, modified).

Shock fronts in air exhibit nearly discontinuous increases in pressure, density, and temperature (Army Materiel Command 1974, p. 1-2).

Shock Velocity: The velocity of the shock front as it travels radially from the burst point. The shock velocity is supersonic, i.e., travels faster than the sonic velocity of the medium (Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency 1997, pp. 5-1 to 5-2).

Also termed shock front velocity.

Side-on Impulse: The integral of side-on pressure over the time interval for which it acts.

Side-on Pressure: (1) The pressure on a surface parallel to the direction of the blast wave propagation (Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency 1997, p. 5-1). (2) The force per unit area that is exerted by a fluid upon a surface at rest relative to the fluid (i.e., surface is moving with the fluid in the direction of measure) (Merriam-Webster n.d., Static Pressure).

Side-on pressure represents the potential energy component (potential energy/unit volume) of a fluid particle and is expressed in typical pressure units of force per area, such as pascals (N/m^2) or psi (lbf/in^2). As defined in Wikipedia, "A [side-on/incident/static] pressure can be identified for every point in a body of fluid, regardless of whether the fluid is in motion." Associated not with the motion of a fluid but with its state (n.d., Static Pressure).

The side-on pressure is named so because it is typically measured with "side-on" pressure transducers, where the sensing element is on the side of the sensor housing and oriented to measure perpendicular to the shock front velocity (flow). The definition of Pressure Pencil Probe in Section 2.4 provides the details of one such pressure transducer. Side-on pressure is also known as "incident" pressure in blast research or experimentation and as "static" pressure in conventional fluid dynamics. By measuring perpendicular to the shock front velocity, the effects of the gross gas motion (dynamic pressure) do not affect the measurement and only the gas at rest relative to the direction of sensing is measured. The "Air Blast" illustration on the left in Fig. 2 provides a depiction of how the side-on pressure is measured in a blast environment and related to the dynamic and total pressures. The figure also includes a correlation to classical fluid dynamic terms on the right to help in comprehension.

Specific Impulse: (1) The integral of pressure over the time interval for which it acts. (2) The area under the curve of the pressure versus time function (also known as pressure-time history).

Quite often Specific Impulse is simply referred to as "impulse" in air blast research and experimentation. This contrasts with classical physics or engineering, where "impulse" is usually reserved for the integral of force (not pressure) over time.

Stagnation Pressure: Sometimes referred to as Pitot Pressure, Total Pressure, or Total Head Pressure. The pressure measured by a stagnation gauge or Pitot tube. Equal to the sum of the side-on pressure and dynamic pressure (Needham 2010, p. 5).

The stagnation pressure is a measure of the total energy density in the flow at the shock front (Needham 2010, pp. 14 to 15). Stagnation pressure is expressed in typical pressure units of force per area, such as pascals (N/m^2) or psi (lbf/in^2), but may be expressed in joules per cubic meter (J/m^3) when representing the energy density.

Many times in blast research, Stagnation Pressure and Total Pressure are used interchangeably since gravitational head, which is an additional term included in the formal definition of total pressure, is often negligible in blast scenarios. This may not be the case in conventional fluid dynamic scenarios.

The definition of Stagnation Gauge in Section 2.4 provides details of how stagnation pressure is measured in a blast environment. The "Air Blast" illustration on the left in Fig. 2 provides a depiction of how the stagnation pressure (labeled as total pressure) is measured in a blast environment and related to the dynamic and side-on pressures. The figure also includes a correlation to classical fluid dynamic terms on the right to help in comprehension.

Time of Arrival: Time when the shock wave from an explosion reaches a location.

Total Pressure: (As related to blast): The sum of side-on and dynamic pressure (see Stagnation Pressure). (Formal): The sum of static pressure, dynamic pressure, and gravitational head (gravitational potential energy/unit vol) as expressed by Bernoulli's principle:

$$P_{\mathrm{t}} = P_s + q + \rho g z$$

where P_t is total pressure, P_s is static pressure (or side-on pressure for blast), q is dynamic pressure, ρ is the density of the fluid, g is the local acceleration due to gravity, and z is the height above a datum. When multiplied together, ρgz is the gravitational head.

Total pressure represents the total energy of a fluid particle. Total energy is constant along a streamline, while incident and dynamic pressures may vary along that same streamline.

If the variation in height above the datum is zero, or so small it can be ignored, the above equation reduces to the following simplified form (Wikipedia n.d.):

$$P_t = P_s + q \qquad \text{(used in air blast)}$$

In most cases of air blast, the pressure change due to gravitational head (a change in streamline elevation) is negligible and the reduced term (sum of side-on and dynamic pressure) is used. This reduced term is known as the stagnation pressure in fluid dynamics. See the definition of Stagnation Pressure for additional details.

Triple Point: The point where the incident, reflected, and Mach shock waves intersect. See Fig. 3 for an illustration.

See incident pressure, reflected pressure, and Mach stem for definitions of each component of the triple point. The reader is referred to the sources provided in Section 3 for more detailed information, with p. 5-12 in TM 5-855-1 providing a nice introduction (Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency 1997).

One method that is often helpful to clarify the pressure terms used in air blast research and experimentation is to relate these to the terms generally used in conventional fluid dynamics. This correlation is demonstrated for principal pressure terms in Table 1.

Table 1 Correlation of air blast to classical fluid dynamics terms

Air blast term(s)	Fluid dynamics term(s)
Side-on pressure, overpressure, incident pressure	Pressure, static pressure
Dynamic pressure	Dynamic pressure
Total pressure	Pitot pressure, stagnation pressure, total pressure[a]
Reflected pressure	Reflected pressure

[a] For case where gravitational head (potential or elevation) is negligible along a streamline.

2.4 Pressure Measurement

A few commonly encountered pressure sensors are presented in this section.

Flush Diaphragm Pressure Transducer: A sensor (transducer) with a sensing element (diaphragm) that is used for measuring pressure and may be mounted flush to the surface of an object (Fig. 6).

Also known as a flush diaphragm pressure sensor. The pressure measured depends on the orientation of the surface to which the sensor is flush-mounted. The sensor is typically used to measure side-on or reflected pressure but can also measure total (stagnation) pressure if mounted in an aerodynamically streamlined housing.

The report *Flush Mounting a Pressure Transducer for Combat Vehicle Ammunition Compartmentation and Survivability Experiments* (Payne 2020) gives details of these sensors and a mount design that provides fragment and blast protection.

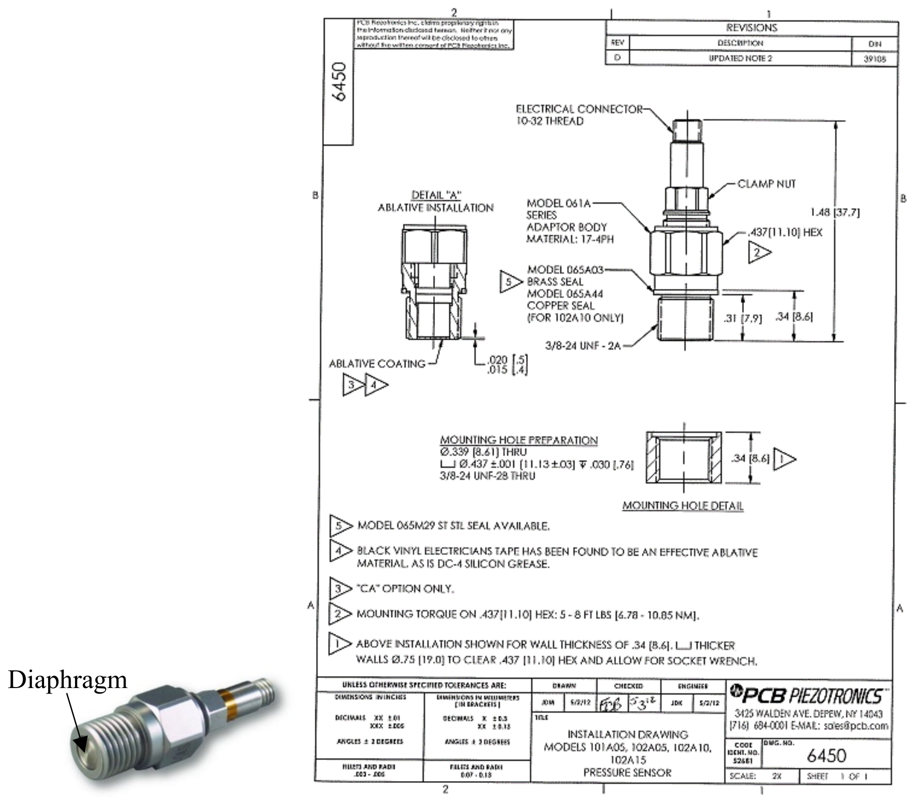


Fig. 6 Example of a flush diaphragm pressure transducer. (Photograph and engineering drawing courtesy of PCB Piezotronics, Inc. Left: https://www.pcb.com/products?m=102a05. Right: PCB Piezotronics. Model 102A05 High Resolution ICP® pressure sensor, 100 psi, 50 mV/psi, 3/8-24 mtg thd, Installation and Operating Manual. https://www.pcb.com/spec_sheet.asp?m=102A05.)

Pressure Pencil Probe: A pressure sensor that is shaped like a pencil and used to measure side-on pressure (Fig. 7).

As defined by Kistler Instrument Corp., the "pencil shape minimizes the influence of the sensor geometry on the blast wave propagation... .[The sensor] is pointed radially at the center of the explosion and measures the side-on pressure of the propagating blast wave" (2014). In other words, the point of the pencil-shaped case should be pointed at the pressure source (explosive). The sensing element is on the side of the pencil-shaped case and measures side-on pressure.

The report *Utilization of Pencil Probes in Blast Experiments for the Explosive Effects Branch* (Showalter 2020) details how these sensors are employed in air blast experiments.

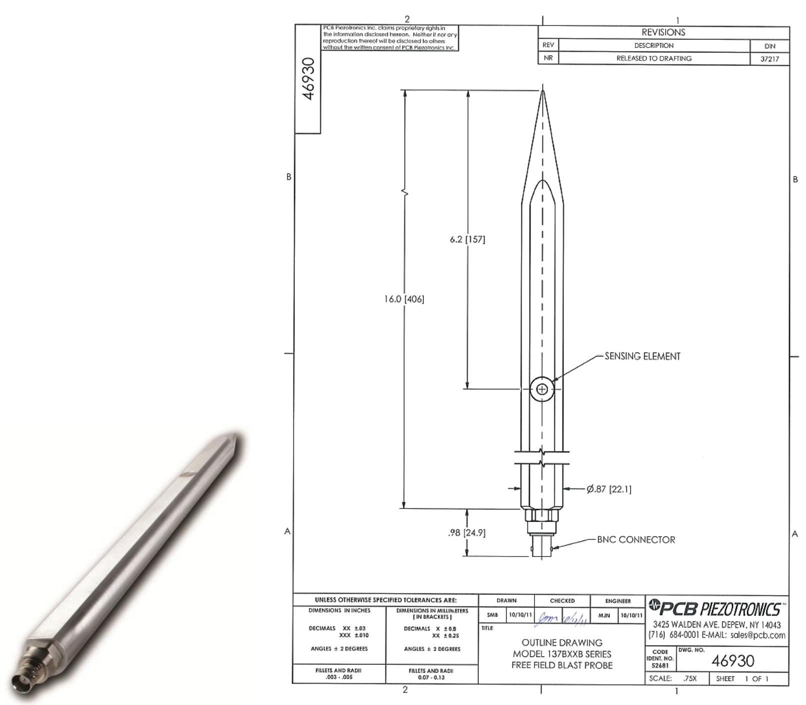
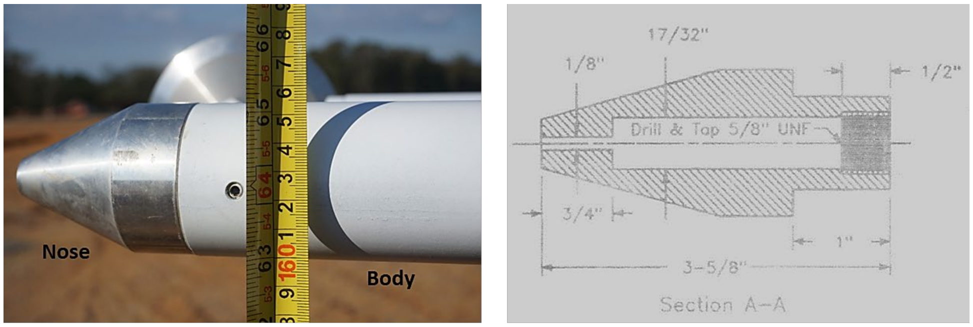


Fig. 7 Example of a pressure pencil probe. (Photograph and engineering drawing courtesy of PCB Piezotronics, Inc. Left: https://www.pcb.com/products?m=137B23B. Right: PCB Piezotronics. Model 137B23B ICP® Pressure Sensor Installation and Operating Manual. https://www.pcb.com/spec_sheet.asp?m=137b23b.)

Stagnation Gauge: A pressure sensor that is used to measure the stagnation pressure.

Measurement of the stagnation pressure is accomplished by inserting a probe into the flow such that the pressure sensing element is oriented opposite to the direction of the flow (Needham 2010, p. 15).

The typical stagnation gauge used in air blast experiments consists of a small flush diaphragm pressure transducer mounted in an aerodynamically streamlined housing. The nose of the housing is pointed directly at the oncoming shock front to stagnate the flow. The pressure sensor is mounted in the nose with the sensing element coaxially aligned towards the oncoming shock front. An example of the streamlined housing of a stagnation gauge is provided in Fig. 8. The flush diaphragm pressure transducer is not shown.



Close up of stagnation gauge — Cross section of nose

Fig. 8 Example of a stagnation gauge (photograph and cross-section engineering drawing courtesy of the US Army Corps of Engineers, Engineer Research and Development Center)

The void in the housing nose where the flush diaphragm pressure transducer is inserted is shown in the cross section in the right view of Fig. 8. The nose of the housing and the sensing element of the pressure transducer, which point in the same direction (towards left in Fig. 8), is pointed at the pressure source to measure the stagnation pressure. The housing is streamlined to minimize pressure reflections while stagnating the flow. Sometimes referred to as a total pressure gauge in blast research.

Total Pressure Gauge: See Stagnation Gauge.

For a more complete history and overview of measurement techniques and instrumentation in air blast research and experimentation, see Chapter 7 of AMC Pamphlet 706-181 (Army Materiel Command 1974) or Chapter 11 of *Blast Waves* (Needham 2010, pp. 139 to 154).

2.5 Fragment and Debris

Fragment: A piece of a weapon that is broken off, detached, or designed to be propelled upon detonation.

Also referred to as a primary fragment to distinguish it from a secondary fragment.

Debris: Also called secondary debris. See Secondary Fragment.

Secondary Fragment: Material propelled by the detonation of an explosive weapon that was not considered part of the original weapon (e.g., piece of a wall, building, spalled or scabbed material, or a nearby object). The material may be propelled directly or indirectly by the effects of the blast and/or primary fragments (Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency 1997, p. 7-31, modified).

Sometimes referred to as a secondary projectile.

Striking Velocity: The velocity of a fragment (primary or secondary) immediately prior to impact with a target.

2.6 Scaling and Computer Programs

Several techniques are used to scale pressure, impulse, distance, or mass of explosive between experiments to normalize for comparison and to make predictions for altered conditions. Fast-running computer programs exist that provide an estimate of useful blast parameters that are derived from scaling techniques, empirical data, or analytical and computational models. Some of the common scaling techniques and computer programs used by EEB are described below. The reader is referred to the references cited for the full information on how to properly use these techniques or programs.

Blast Scaling: The relation of air blast parameters under a known condition to their values or state under an altered (scaled) condition.

Per Needham, "It is often useful to be able to scale the results from one experiment to a similar experiment having a different yield. Such scaling allows the pressure or impulse from one experiment to be used to predict the pressure from another or to compare the results of two different experiments" (2010, p. 157).

BlastX: Computer program that provides the internal air blast environment in multi-room structures for both internal and external explosions using fast running analytical/empirical models (Britt et al. 2001).

BlastX is a prominent program used for estimating the "propagation of blast shock waves and detonation products gases in multi-room structures... ." (Britt et al. 2001, p. 1). The program uses a combination of semi-empirical models and hydrocode calculations. The latest version of the program, updated in 2019, is maintained by the US Army Corps of Engineers (USACE) and includes a user-friendly graphical user interface (GUI). See Britt et al. (2001) or visit the USACE Protective Design Center homepage[*] for more information.

ConWep: Computer program that performs a variety of conventional weapons effects calculations, including an assortment of airblast routines, fragment, and projectile penetrations, cratering, and ground shock (Hyde 1988).

One of the EEB uses of the program is to provide estimates of pressure, impulse, time of arrival, and a variety of other metrics from a given mass of explosive. ConWep is well suited for free-field estimates of free-air burst and surface burst charges. The ConWep program was created by the USACE, Engineer Waterways

[*] https://www.nwo.usace.army.mil/About/Centers-of-Expertise/Protective-Design-Center/

Experiment Station in 1987 and is primarily based off TM 5-855-1 (Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency 1997). The major routines of ConWep were written in ANSI standard FORTRAN-77 (Hyde 1988, p. 7), and a GUI provides user-friendly execution of the program (updated in 2005). The program is still maintained by USACE. See Hyde (1988) or visit the USACE Protective Design Center homepage* for more information.

Cube-Root Scaling: see Hopkinson Scaling.

Hopkinson Scaling: Law [that states] self-similar blast (shock) waves are produced at identical scaled distances when two explosive charges of similar geometry and the same explosive composition, but of different size, are detonated in the same atmosphere (Army Materiel Command 1974, p. 3-2).

The following equation is used in Hopkinson scaling:

$$\frac{R}{R_2} = \left(\frac{W}{W_2}\right)^{0.333} \quad or \quad \frac{R}{W^{0.333}} = \frac{R_2}{W_2^{0.333}}$$

where W = reference explosive mass (kg)

W_2 = different explosive mass (kg)

R = distance from detonation point of W (m)

R_2 = distance from detonation point of W_2 (m)

The Hopkinson scaling law states that the values of certain characteristic properties (such as side-on pressure, dynamic pressure, and particle velocity) at a particular distance from one explosion can be expected at a different distance from another explosion of different mass but of the same explosive composition, same charge shape, and under the same atmospheric conditions. See the *Engineering Design Handbook* (Army Materiel Command 1974, pp. 3-2 to 3-3) and TM 5-855-1 (Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency 1997, p. 5-5) for more information. A useful graphic of this scaling is shown in Fig. 9; note the circle on the left is the explosive charge (denoted with diameter d).

The bottom illustration in Fig. 9 represents the scenario as scaled by a factor, K.

* https://www.nwo.usace.army.mil/About/Centers-of-Expertise/Protective-Design-Center/

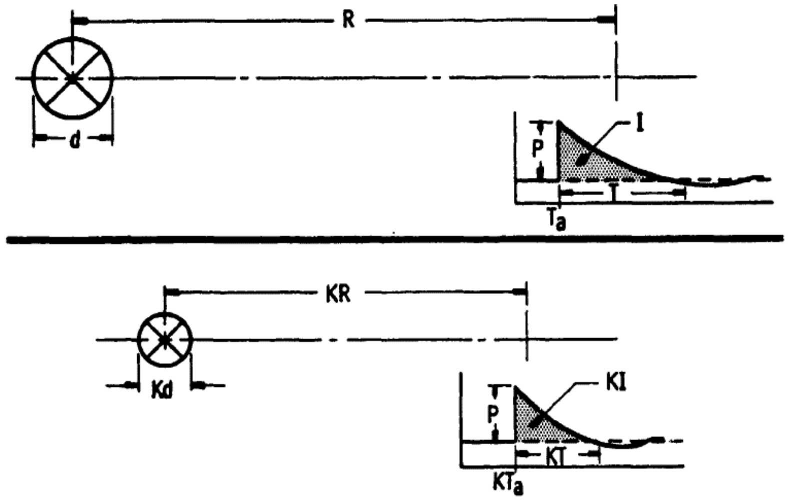


Fig. 9 Hopkinson blast wave scaling (Army Materiel Command 1974, Fig. 3-1)

The total energy of the explosive may be substituted for the explosive mass in the Hopkinson scaling equation when scaling with this law. Page 3-3 in AMC Pamphlet 706-181 (Army Materiel Command 1974) describes the benefits of scaling with energy instead of the mass of the explosive. However, when dealing with most conventional weapons, using the mass of the explosive to scale is sufficient, easier, and more common.

Scaling: see Blast Scaling.

Sachs Scaling: [Law that] states 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 (Department of Energy 1992, p. 4-10).

This is a more general scaling law than Hopkinson and accounts for differences in atmospheric conditions. Per the Department of Energy, Sachs' scaling is "almost universally used to predict characteristics of blast waves from explosions at high altitude" (1992, p. 4-10). Scaling with this law requires the calculation of a pressure, distance, time, and impulse scaling factor for charges with different explosive masses and at different altitudes (atmospheric conditions) but of the same explosive composition and same charge shape. See Section 3-2.2 in *Engineering Design Handbook* (Army Materiel Command 1974) and Section 5.2.1.2.2 in TM 5-855-1 (Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency 1997) for more information.

TNT Equivalence: The mass of trinitrotoluene (TNT) in kilograms which when detonated will produce the same free-air property as one kilogram of the explosive in question (Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency 1997, p. 4-9). The free-air property is typically peak pressure or peak impulse.

TNT equivalency is used to compare explosives of different compositions. The TNT equivalency for pressure is usually different than that for impulse for the same explosive. Table 5-1 (pp. 5-15 to 5-16) in TM 5-855-1 lists the TNT equivalent mass for pressure and impulse in free air for several explosive types. The TNT equivalency also depends on range from the explosive and there are several restrictions. See Sections 4.3.1 (p. 4-9) and 5.2.2.1 (p. 5-14) in TM 5-855-1 for more information (Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency 1997).

Equivalency may also be determined using other unit systems, such as US Customary (lbf), provided the amount of explosive in question and the equivalent amount of TNT are compared in the same unit system.

3. Useful References for an Introduction to Air Blast

This section provides a list of references that are often found useful to those just beginning in the technical area of air blast. These references are also useful to more advanced users, as the later chapters cover advanced topics in air blast.

Engineering Design Handbook. Explosions in Air. Part 1. Army Materiel Command. July 1974. AMC Pamphlet 706-181. DTIC Accession Number: ADA003817.

Technical Manual: Design and Analysis of Hardened Structures to Conventional Weapons Effects. Departments of the Army, Air Force, and Navy and the Defense Special Weapons Agency. Dec. 1997. Army TM 5-855-1. DTIC Accession Number: ADB237497.

A Manual for the Prediction of Blast and Fragment Loadings on Structures. United States Department of Energy, Albuquerque Operations Office. July. 1992. DOE/TIC-11268. DTIC Accession Number: ADB170242.

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List of Symbols, Abbreviations, and Acronyms

ARL	Army Research Laboratory
DEVCOM	US Army Combat Capabilities Development Command
EEB	Explosive Effects Branch
GUI	graphical user interface
S.O.	standoff
TNT	trinitrotoluene
USACE	US Army Corps of Engineers

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