This chapter discusses blast effects, potential school damage, injuries, levels of protection, stand-off distance, and predicting blast effects. Specific blast design concerns and mitigation measures are discussed in Chapters 2 and 3. Explosive events have historically been a favorite tactic of terrorists for a variety of reasons and this is likely to continue into the future. The DoD, GSA, and DOS have considerable experience with blast effects and blast mitigation. However, many architects and building designers do not have such experience. For additional information on explosive blast, see FEMA 426, *Reference Manual to Mitigate Potential Terrorist Attacks Against Buildings*, and FEMA 427, *Primer for Design of Commercial Buildings to Mitigate Terrorist Attacks*. See sidebar for important reference material on explosive blast.

The following additional references are recommended:

- Air Force Engineering and Services Center. Protective Construction Design Manual, ESL-TR-87-57. Prepared for Engineering and Services Laboratory, Tyndall Air Force Base, FL. (1989).
- U.S. Department of the Army. Security Engineering, TM 5-853 and Air Force AFMAN 32-1071, Volumes 1, 2, 3, and 4. Washington, DC, Departments of the Army and Air Force. (1994).
- U.S. Department of the Army. Structures to Resist the Effects of Accidental Explosions, Army TM 5-1300, Navy NAVFAC P-397, AFR 88-2. Washington, DC, Departments of the Army, Navy, and Air Force. (1990).
- U.S. Department of Energy. A Manual for the Prediction of Blast and Fragment Loading on Structures, DOE/TIC 11268. Washington, DC, Headquarters, U.S. Department of Energy. (1992).
- U.S. General Services Administration. GSA Security Reference Manual: Part 3 Blast Design and Assessment Guidelines. (2001).
- Biggs, John M. Introduction to Structural Dynamics. McGraw-Hill. (1964).
- The Institute of Structural Engineers. The Structural Engineer's Response to Explosive Damage. SETO, Ltd., 11 Upper Belgrave Street, London SW1X8BH. (1995).
- Mays, G.S. and Smith, P.D. Blast Effects on Buildings: Design of Buildings to Optimize Resistance to Blast Loading. Thomas Telford Publications, 1 Heron Quay, London E14 4JD. (1995).
- National Research Council. Protecting Buildings from Bomb Damage. National Academy Press. (1995).

4.1 BLAST EFFECTS

An explosion is an extremely rapid release of energy in the form of light, heat, sound, and a shock wave. A shock wave consists of highly compressed air traveling radially outward from the source at supersonic velocities. As the shock wave expands, pressures decrease rapidly (with the cube of the distance) and, when it meets a surface that is in line-of-sight of the explosion, it is reflected and amplified by a factor of up to thirteen. Pressures also decay rapidly over time (i.e., exponentially) and have a very brief span of existence, measured typically in thousandths of a second, or milliseconds. Diffraction effects, caused by corners of a building, may act to confine the air-blast, prolonging its duration. Late in the explosive event, the shock wave becomes negative, creating suction. Behind the shock wave, where a vacuum has been created, air rushes in, creating a powerful wind or drag pressure on all surfaces of the building. This wind picks up and carries flying debris in the vicinity of the detonation. In an external explosion, a portion of the energy is also imparted to the ground, creating a crater and generating a ground shock wave analogous to a high-intensity, short-duration earthquake.

In the context of other hazards (e.g., earthquakes, winds, or floods), an explosive attack has the following distinguishing features:

- The intensity of the pressures acting on a targeted building can be several orders of magnitude greater than these other hazards. It is not uncommon for the peak pressure to be in excess of 100 pounds per square inch (psi) on a building in an urban setting for a vehicle weapon parked along the curb. At these pressure levels, major damages and failure are expected.
- Explosive pressures decay extremely rapidly with distance from the source. Therefore, the damages on the side of the building facing the explosion may be significantly more severe than on the opposite side. As a consequence, direct air-blast damages tend to cause more localized damage.
- The duration of the event is very short, measured in thousandths of a second, or milliseconds. This differs from earthquakes and wind gusts, which are measured in seconds, or sustained wind or flood situations, which may be measured in hours. Because of this, the mass of the structure has a strong mitigating effect on the response because it takes time to mobilize the mass of the structure. By the time the mass is mobilized, the loading is gone, thus mitigating the response. This is the opposite of earthquakes, whose imparted forces are roughly in the same timeframe as the response of the building mass, causing a resonance effect that can worsen the damage.

4.1.1 Building Damage

The extent and severity of damage and injuries in an explosive event cannot be predicted with perfect certainty. Past events show that the unique specifics of the failure sequence for a building significantly affect the level of damage. Despite these uncertainties, it is possible to give some general indications of the overall level of damage and injuries to be expected in an explosive event, based on the size of the explosion, distance from the event, and assumptions about the construction of the building.

Damage due to the air-blast shock wave may be divided into direct air-blast effects and progressive collapse. Direct air-blast effects are damage caused by the high-intensity pressures of the air-blast close in to the explosion and may induce the localized failure of exterior walls, windows, floor systems, columns, and girders. Progressive collapse is discussed in Section 3.2.

The air-blast shock wave is the primary damage mechanism in an explosion. The pressures it exerts on building surfaces may be several orders of magnitude greater than the loads for which the building is designed. The shock wave also acts in directions that the building may not have been designed for, such as upward on the floor system. In terms of sequence of response, the air-blast first impinges on the weakest point in the vicinity of the device closest to the explosion, typically the exterior envelope of the building. The explosion pushes on the exterior walls at the lower stories and may cause wall failure and window breakage. As the shock wave continues to expand, it enters the structure, pushing both upward and downward on the floors (see Figure 4-1).

Floor failure is common in large-scale vehicle-delivered explosive attacks, because floor slabs typically have a large surface area for the pressure to act on and a comparably small thickness. In terms of the timing of events, the building is engulfed by the shockwave and direct air-blast damage occurs within tens to hundreds of milliseconds from the time of detonation. If progressive collapse is initiated, it typically occurs within seconds.

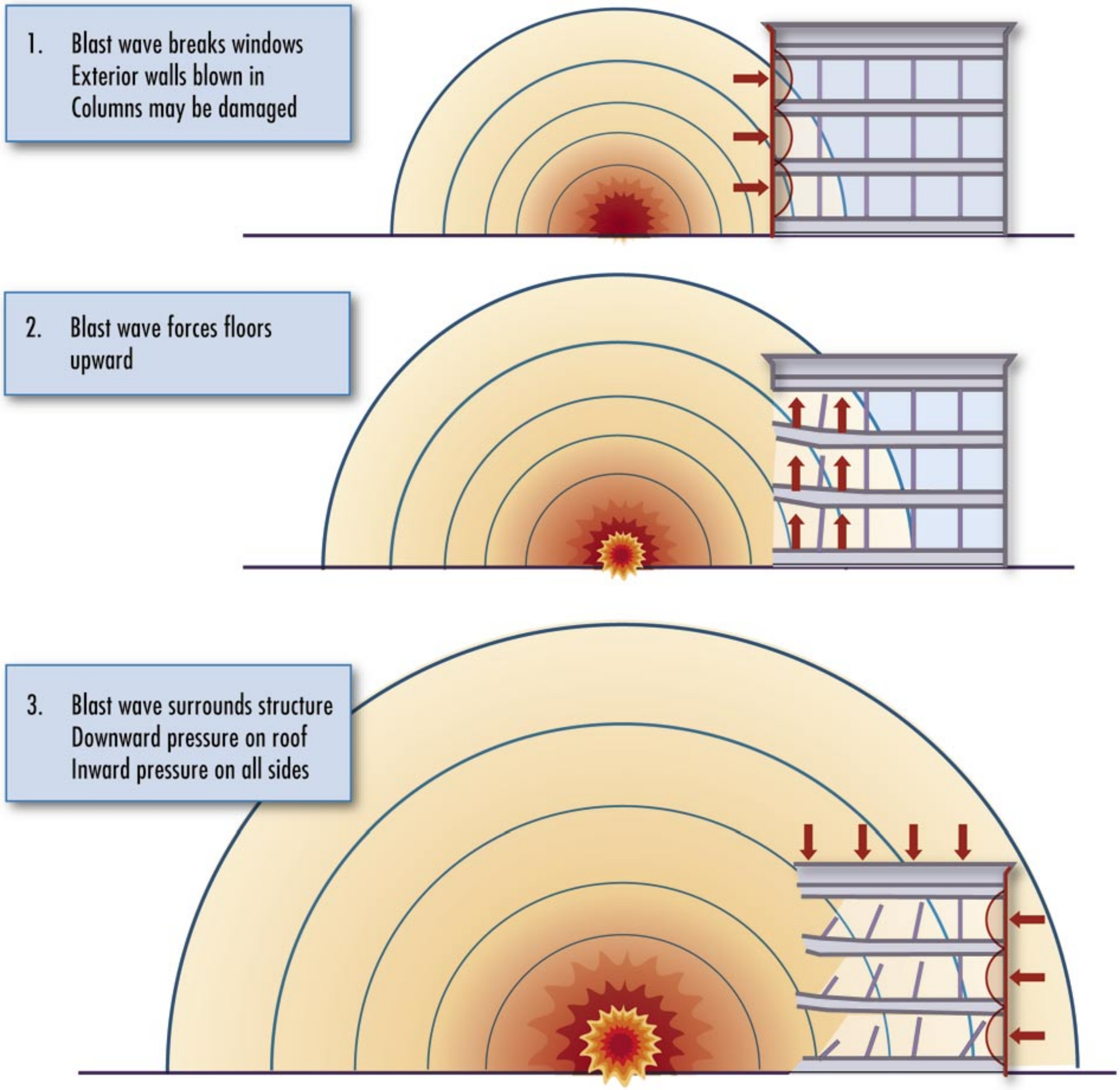

Figure 4-1 Blast pressure effects on a structure

Glass is often the weakest part of a building, breaking at low pressures compared to other components such as the floors, walls, or columns. Past incidents have shown that glass breakage may extend for miles in large external explosions. High-velocity glass fragments have been shown to be a major contributor to injuries in such incidents. For incidents within downtown city areas, falling glass poses a major hazard to passersby on the sidewalks below and prolongs post-incident rescue and cleanup efforts by leaving tons of glass debris on the street. Specific glazing design considerations are discussed in Chapter 3.

4.1.2 Casualties and Injuries

Blast can cause significant casualties. During the bombing of the Murrah Federal Building, 168 people were killed. Severity and type of injury patterns incurred in explosive events may be related to the level of structural damage. The high pressure of the air-blast that enters through broken windows can cause eardrum damage and lung collapse. As the air-blast damages the building components in its path, missiles are generated that cause impact injuries. Airborne glass fragments typically cause penetration or laceration-type injuries. Larger fragments may cause non-penetrating, or blunt trauma, injuries. Finally, the air-blast pressures can cause occupants to be bodily thrown against objects or to fall. Lacerations due to high-velocity flying glass fragments have been responsible for a significant portion of the injuries received in explosion incidents. In the bombing of the Murrah Federal Building in Oklahoma City, for instance, 40 percent of the survivors in the building cited glass as contributing to their injuries. Within nearby buildings, laceration estimates ranged from 25 percent to 30 percent.

4.1.3 Levels of Protection

The amount of explosive and the resulting blast dictate the level of protection required to prevent a building from collapsing or minimize injuries and deaths. Table 4-1 shows how the DoD correlates levels of protection with potential damage and expected injuries. The GSA and the Interagency Security Committee (ISC) also use the level of protection concept. However, wherein DoD has five levels, they have established four levels of protection. The GSA and ISC levels of protection can be found in GSA PBS-P100, *Facilities Standards for the Public Buildings* Service, November 2000, Section 8.6.

Table 4-1: DoD Minimum Antiterrorism (AT) Standards for New Buildings

Level of Protection	Potential Structural Damage	Potential Door and Glazing Hazards	Potential Injury
Below AT standards	Severely damaged – frame collapse/massive destruction. Little left standing.	Doors and windows fail and result in lethal hazards	Majority of personnel suffer fatalities.
Very Low	Heavily damaged – onset of structural collapse. Major deformation of primary and secondary structural members, but progressive collapse is unlikely. Collapse of non-structural elements.	Glazing will break and is likely to be propelled into the building, resulting in serious glazing fragment injuries, but fragments will be reduced. Doors may be propelled into rooms, presenting serious hazards.	Majority of personnel suffer serious injuries. There are likely to be a limited number (10 percent to 25 percent) of fatalities.
Low	Damaged – unrepairable. Major deformation of non-structural elements and secondary structural members and minor deformation of primary structural members, but progressive collapse is unlikely.	Glazing will break, but fall within 1 meter of the wall or otherwise not present a significant fragment hazard. Doors may fail, but they will rebound out of their frames, presenting minimal hazards.	Majority of personnel suffer significant injuries. There may be a few (<10 percent) fatalities.
Medium	Damaged – repairable. Minor deformations of non-structural elements and secondary structural members and no permanent deformation in primary structural members.	Glazing will break, but will remain in the window frame. Doors will stay in frames, but will not be reusable.	Some minor injuries, but fatalities are unlikely.
High	Superficially damaged. No permanent deformation of primary and secondary structural members or non-structural elements.	Glazing will not break. Doors will be reusable.	Only superficial injuries are likely.

SOURCE: THE DoD UNIFIED FACILITIES CRITERIA (UFC), *DoD MINIMUM ANTITERRORISM STANDARDS FOR BUILDINGS*, UFC 4-010-01, 31 JULY 2002

The levels of protection above can roughly be correlated for conventional construction without any blast hardening to the following incident pressures as shown in Table 4-2.

Table 4-2: Correlation of DoD Level of Protection to Incident Pressure

Level of Protection	Incident Pressure (psi)
High	1.1
Medium	1.8
Low	2.3

Figure 4-2 shows an example of a range-to-effect chart that indicates the distance or stand-off to which a given size bomb will produce a given effect (see Section 4.2). This type of chart can be used to display the blast response of a building component or window at different levels of protection. It can also be used to consolidate all building response information to assess needed actions if the threat weapon-yield changes. For example, an amount of explosives are stolen and indications are that they may be used against a specific building. A building-specific range-to-effect chart will allow quick determination of the needed stand-off for the amount of explosives in question, once the explosive weight is converted to trinitrotoluene (TNT) equivalence. Given an explosive weight and a stand-off distance, Figure 4-2 can be used to predict damage for nominal building construction.

For design purposes, large scale truck bombs typically contain 10,000 pounds or more of TNT equivalent, depending on the size and capacity of the vehicle used to deliver the weapon. Vehicle bombs that utilize vans down to small sedans typically contain 4,000 to 500 pounds of TNT equivalent, respectively. A briefcase bomb is approximately 50 pounds, and a pipe bomb is generally in the range of 5 pounds of TNT equivalent. Research performed as part of the threat assessment process should identify bomb sizes used in the locality or region. Security consultants have valuable information that may be used to evaluate the range of likely charge weights.

Figures 4-3 and 4-4 show blast effects predictions for a high school based on a typical car bomb, and a typical large truck bomb detonated in the school's parking lot, respectively. A computer-based GIS was used to analyze the school's vehicular access and circulation pattern to determine a reasonable detonation point for a vehicle bomb. Structural blast analysis was then performed using nominal explosive weights and a nominal school structure. The results are shown in Figures 4-3 and 4-4. The red ring indicates the area in which structural damage is predicted. The orange and yellow rings indicate predictions for lethal injuries and severe injuries from glass, respectively. Please note that nominal inputs were used in this analysis and they are not a predictive examination.

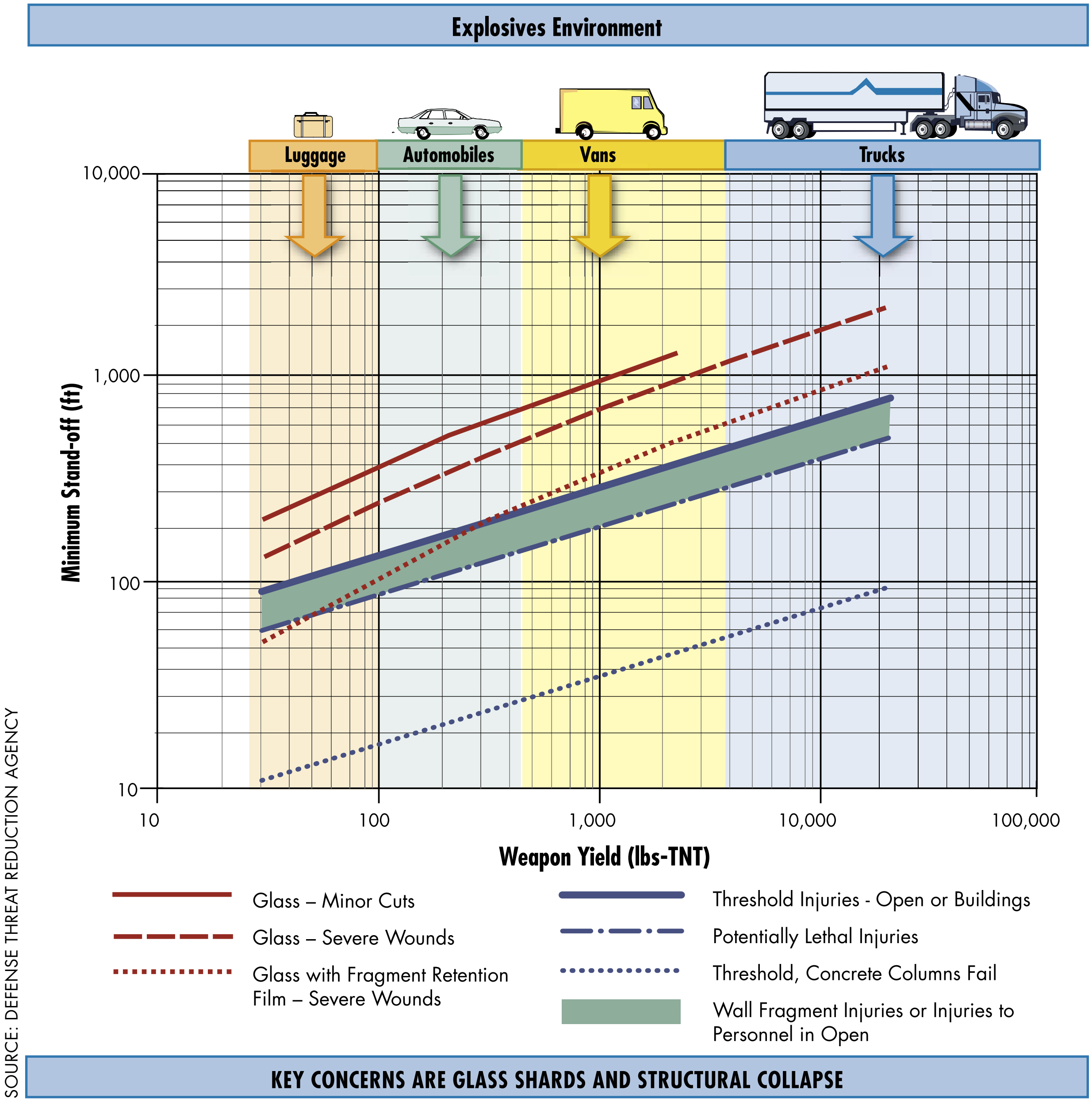

Figure 4-2 Explosives environments - blast range to effects

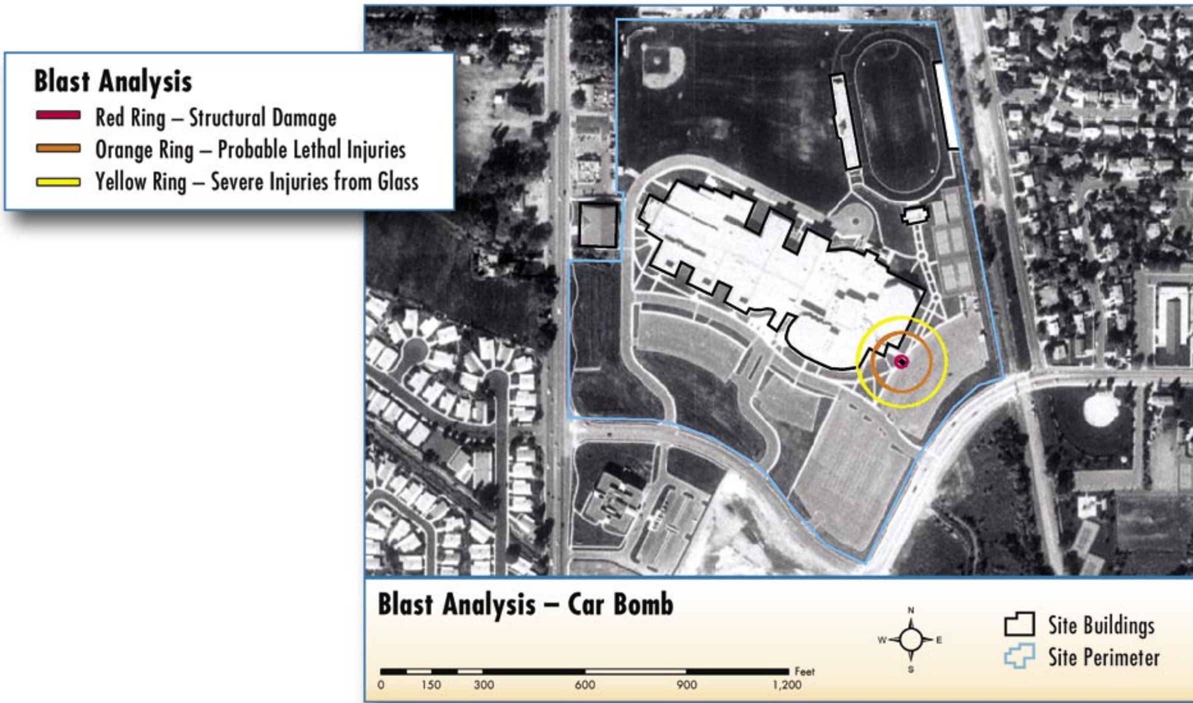

Figure 4-3 Blast analysis of a high school for a typical car bomb detonated in the school's parking lot

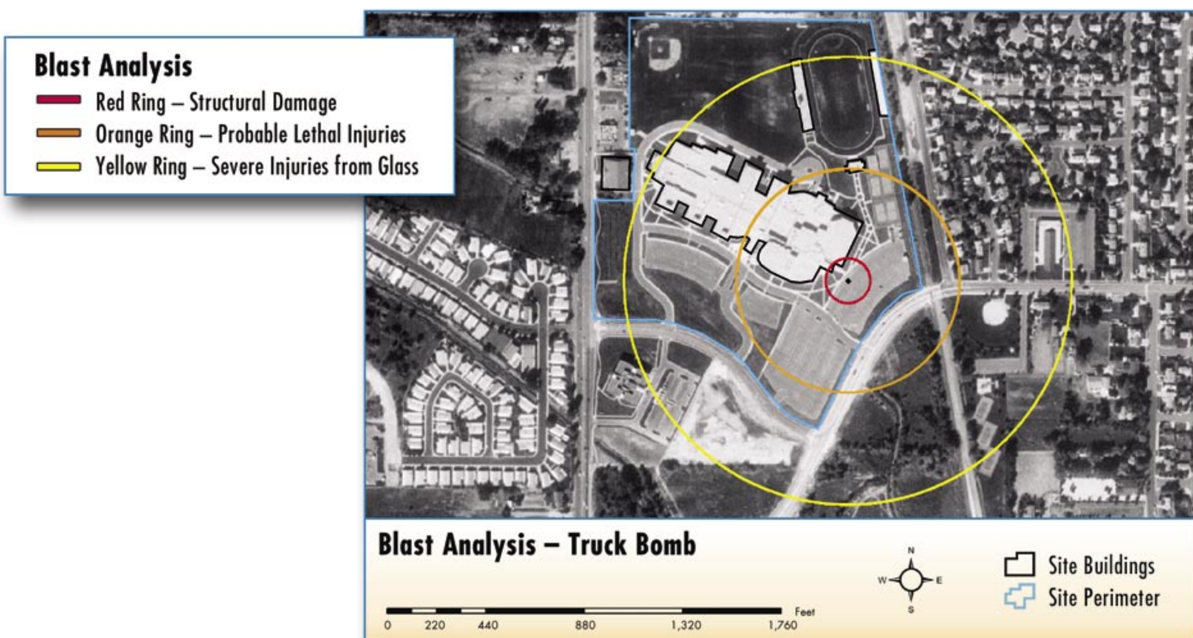

Figure 4-4 Blast analysis of a high school for a typical large truck bomb detonated in the school's parking lot

In the case of a stationary vehicle bomb, knowing the size of the bomb (TNT equivalent in weight), its distance from the structure, how the structure is put together, and the materials used for walls, framing, and glazing allows the designer to determine the level of damage that will occur and the level of protection achieved. Whether an existing building or a new construction, the designer can then select mitigation measures as presented in this chapter and Chapters 2 and 3 to achieve the level of protection desired.

4.2 STAND-OFF DISTANCE AND THE EFFECTS OF BLAST

Energy from a blast decreases rapidly over distance. In general, the cost to provide asset protection will decrease as the distance between an asset and a threat increases, as shown in Figure 4-5. However, increasing stand-off also requires more land and more perimeter to secure with barriers, resulting in an increased cost not reflected in Figure 4-5. As stand-off increases, blast loads generated by an explosion decrease and the amount of hardening necessary to provide the required level of protection decreases.

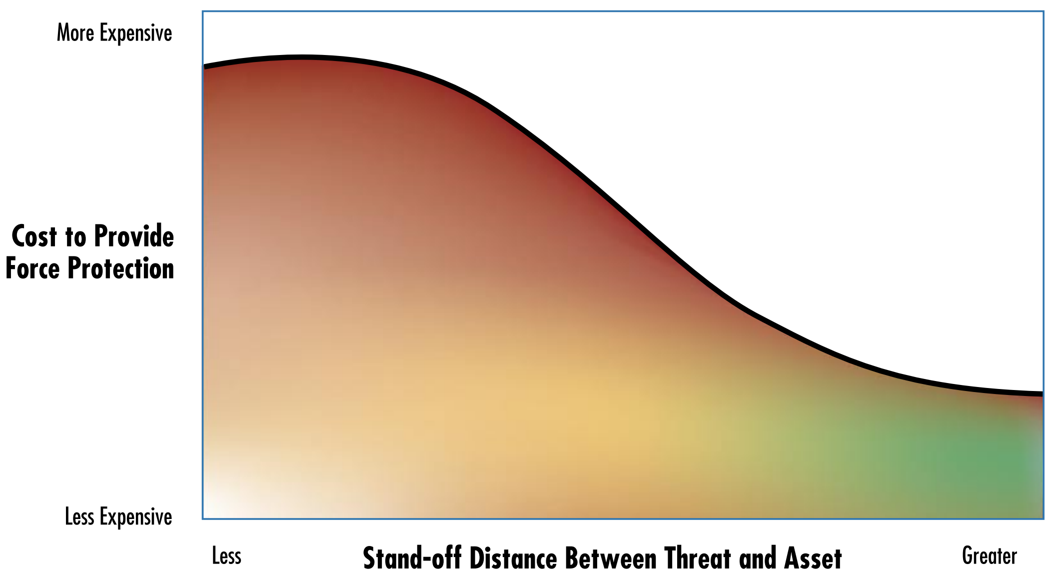

Figure 4-5 Relationship of cost to stand-off distance
SOURCE: U.S. AIR FORCE, *INSTALLATION FORCE PROTECTION GUIDE*

The critical location of the weapon is a function of the site, the building layout, and the security measures in place. For vehicle bombs, the critical locations are considered to be at the closest point that a vehicle can approach on each side, assuming that all security measures are in place. Typically this is a vehicle parked along the curb directly outside the building, or at the entry control point where inspection takes place. For internal weapons, location is dictated by the areas of the building that are publicly accessible (e.g., lobbies, corridors, auditoriums, cafeterias, or gymnasiums). Range or stand-off is measured from the center of gravity of the charge located in the vehicle or other container to the building component under consideration.

Defining appropriate stand-off distance for a given building component to resist explosive blast effects is difficult. Often in urban settings, it is either not possible or practical to obtain appropriate stand-off distance. Adding to the difficulty is the fact that defining appropriate stand-off distance requires a prediction of the explosive weight of the weapon. In the case of terrorism, this is tenuous at best.

The DoD prescribes minimum stand-off distances based on the required level of protection. Where minimum stand-off distances are met, conventional construction techniques can be used with some modifications. In cases where the minimum stand-off cannot be achieved, the building must be hardened to achieve the required level of protection (see the DoD UFC – *DoD Minimum Antiterrorism Standards for Buildings*, UFC 4-010-01, 31 July 2002).

The first step in predicting blast effects on a building is to predict blast loads on the structure. Because blast pressure pulse varies based on stand-off distance, angle of incidence, and reflected pressure over the exterior of the building, the blast load predictions can be very complex. Consultants may use sophisticated methods such as Computational Fluid Dynamics (CFD) computer programs to predict blast loads. These complex programs require special equipment and training to run.

In most cases, especially for design purposes, more simplified methods may be used by blast consultants to predict blast loads. Tables of pre-determined values (see *GSA Security Reference Manual: Part 3 – Blast Design & Assessment Guidelines,* July 31, 2001) or computer programs may be used such as: [1]

- ATBLAST (GSA)
- CONWEP (U.S. Army Engineer Research and Development Center)

Figure 4-6 provides a quick method for predicting the expected overpressure (expressed in pounds per square inch or psi) on a building for a specific explosive weight and stand-off distance. Enter the x-axis with the estimated explosive weight a terrorist might use and the y-axis with a known stand-off distance from a building. By correlating the resultant effects of overpressure with other data, the degree of damage that the various components of a building might receive can be estimated. The vehicle icons in Figure 4-6 indicate the relative size of the vehicles that might be used to transport various quantities of explosives.

The analysis of structures subjected to the effects of an explosion is very complex and requires an understanding of structural engineering, dynamics, strengths of materials, and specialized training in explosive effects. Such analysis should be performed by engineers who can conduct a complex analysis that is both time-dependent and accounts for non-linear behavior. In the absence of such an analysis of a specific structure, it is possible to provide rough approximations of building damages to be expected in an explosive event. Table 4-3 provides basic estimates of incident pressures at which different types of damage generally occur to buildings based on the incident pressures determined in Figure 4-6.

[1] For security reasons, the distribution of these computer programs is limited.

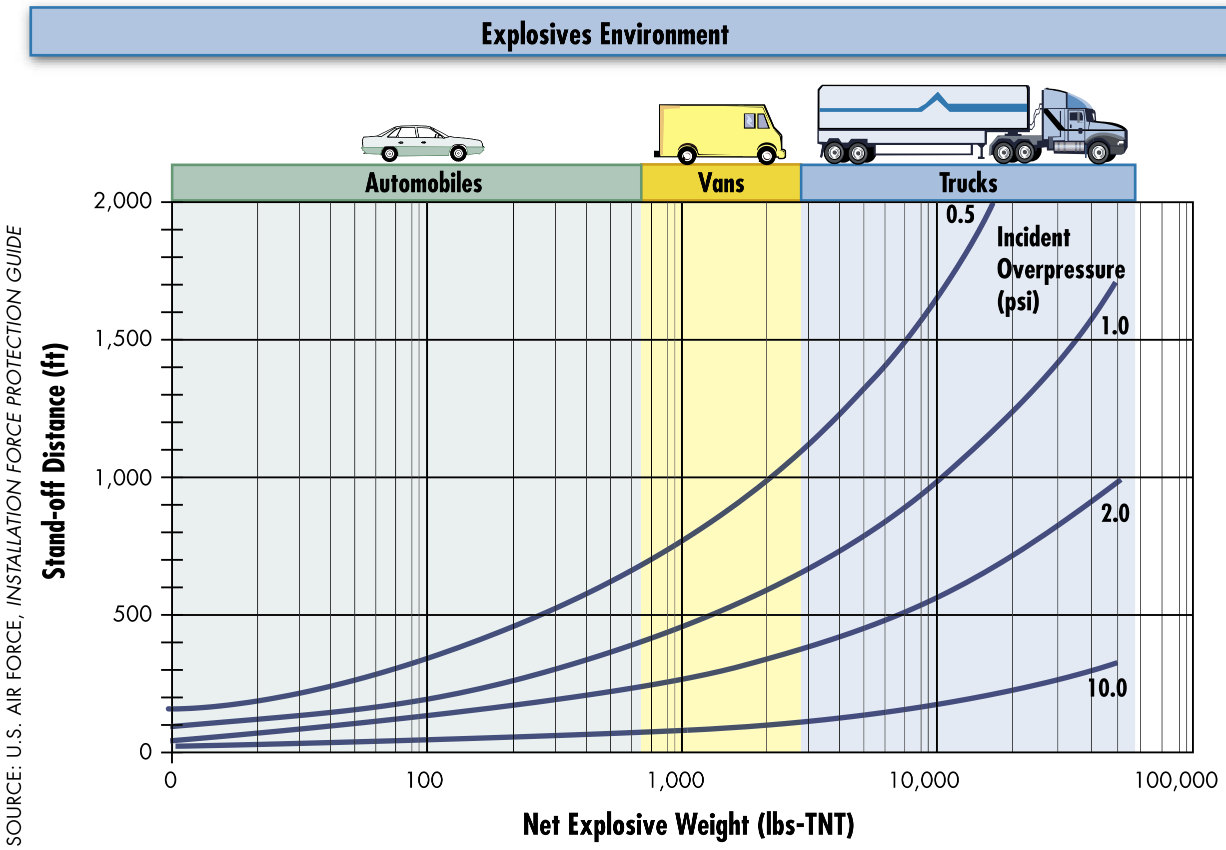

Figure 4-6 Incident overpressure measured in pounds per square inch, as a function of stand-off distance and net explosive weight (pounds-TNT)

Table 4-3: Damage Approximations

Damage	Incident Overpressure (psi)
Typical window glass breakage	0.15 – 0.22
Minor damage to some buildings	0.5 – 1.1
Panels of sheet metal buckled	1.1 – 1.8
Failure of concrete block walls	1.8 – 2.9
Collapse of wood framed buildings	Over 5.0
Serious damage to steel framed buildings	4 – 7
Severe damage to reinforced concrete structures	6 – 9
Probable total destruction of most buildings	10 – 12

SOURCES: *EXPLOSIVE SHOCKS IN AIR*, KINNEY & GRAHM, 1985; *FACILITY DAMAGE AND PERSONNEL INJURY FROM EXPLOSIVE BLAST*, MONTGOMERY & WARD, 1993; AND *THE EFFECTS OF NUCLEAR WEAPONS*, 3RD EDITION, GLASSTONE & DOLAN, 1977.