# EXPLOSIVE BLAST 4

This chapter discusses blast effects, building 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. Ingredients for homemade bombs are easily obtained on the open market as are the techniques for making bombs. Also, explosive events are easy and quick to execute. Vehicle bombs have the added advantage of being able to bring a large quantity of explosives to the doorstep of the target undetected. Finally, terrorists often attempt to use the dramatic component of explosions, in terms of the sheer destruction they cause, to generate media coverage in hopes of transmitting their political message to the public. 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 427, *Primer for Design of Commercial Buildings to Mitigate Terrorist Attacks.*

## 4.1 BLAST EFFECTS

When a high order explosion is initiated, a very rapid exothermic chemical reaction occurs. As the reaction progresses, the solid or liquid explosive material is converted to very hot, dense, high-pressure gas. The explosion products initially expand at very high velocities in an attempt to reach equilibrium with the surrounding air, causing a shock wave. A shock wave consists of highly compressed air, traveling radially outward from the source at supersonic velocities. Only one-third of the chemical energy available in most high explosives is released in the detonation process. The remaining two-thirds is released more slowly as the detonation products mix with air and burn. This afterburning process has little effect on the initial blast wave because it occurs much slower than the original detonation. However, later stages of the blast wave can be affected by the afterburning, particularly for explosions in confined spaces. As the shock wave expands, pressures decrease rapidly (with the cube of the distance) because of geometric divergence and the dissipation of energy in heating the air. 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 . An explosion can be visualized as a “bubble” of highly compressed air that expands until reaching equilibrium with the surrounding air.

Explosive detonations create an incident blast wave, characterized by an almost instantaneous rise from atmospheric pressure to a peak overpressure. As the shock front expands pressure decays back to ambient pressure, a negative pressure phase occurs that is usually longer in duration than the positive phase as shown in Figure 4-1. The negative phase is usually less important in a design than the positive phase.

When the incident pressure wave impinges on a structure that is not parallel to the direction of the wave’s travel, it is reflected and reinforced, producing what is known as reflected pressure. The

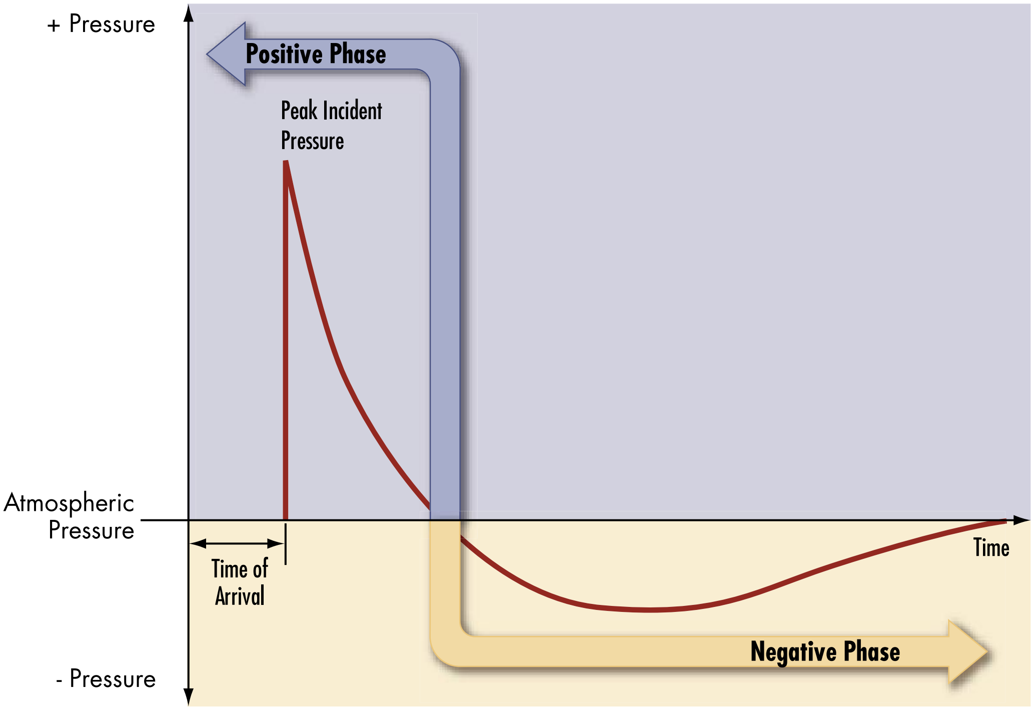


Figure 4-1 Typical pressure-time history

reflected pressure is always greater than the incident pressure at the same distance from the explosion. The reflected pressure varies with the angle of incidence of the shock wave. When the shock wave impinges on a surface that is perpendicular to the direction it is traveling, the point of impact will experience the maximum reflected pressure. When the reflecting surface is parallel to the blast wave, the minimum reflected pressure or incident pressure will be experienced. In addition to the angle of incidence, the magnitude of the peak reflected pressure is dependent on the peak incident pressure, which is a function of the net explosive weight and distance from the detonation.

Figure 4-2 shows typical reflected pressure coefficients versus the angle of incidence for four different peak incident pressures. The reflected pressure coefficient equals the ratio of the peak reflected pressure to the peak incident pressure (Cr = Pr / Pi). This figure shows that reflected pressures for explosive detonations

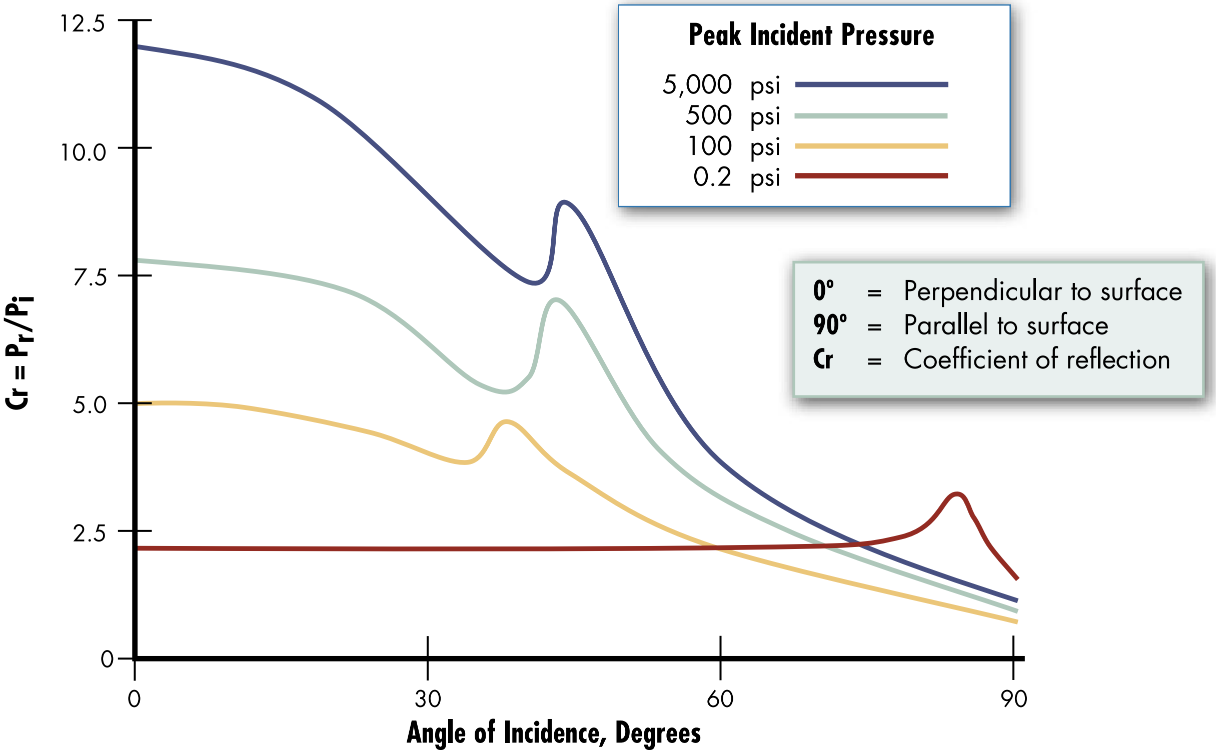


Figure 4-2 Reflected pressure coefficient vs. angle of incidence

can be almost 13 times greater than peak incident pressures and, for all explosions, the reflected pressure coefficients are significantly greater closer to the explosion.

The integrated area under the pressure verse time function is known as the impulse:

$$I = \int P(t)dt$$

I = impulse (psi-ms or Mpa-ms)

P = Pressure (psi or MPa)

T = time (ms)

Impulse is a measure of the energy from an explosion imparted to a building. Both the negative and positive phases of the pressure-time waveform contribute to impulse. Figure 4-3 shows how impulse and pressure vary over time from a typical explosive detonation. The magnitude and distribution of blast loads on a structure vary greatly with several factors:

- Explosive properties (type of material, energy output, and quantity of explosive)

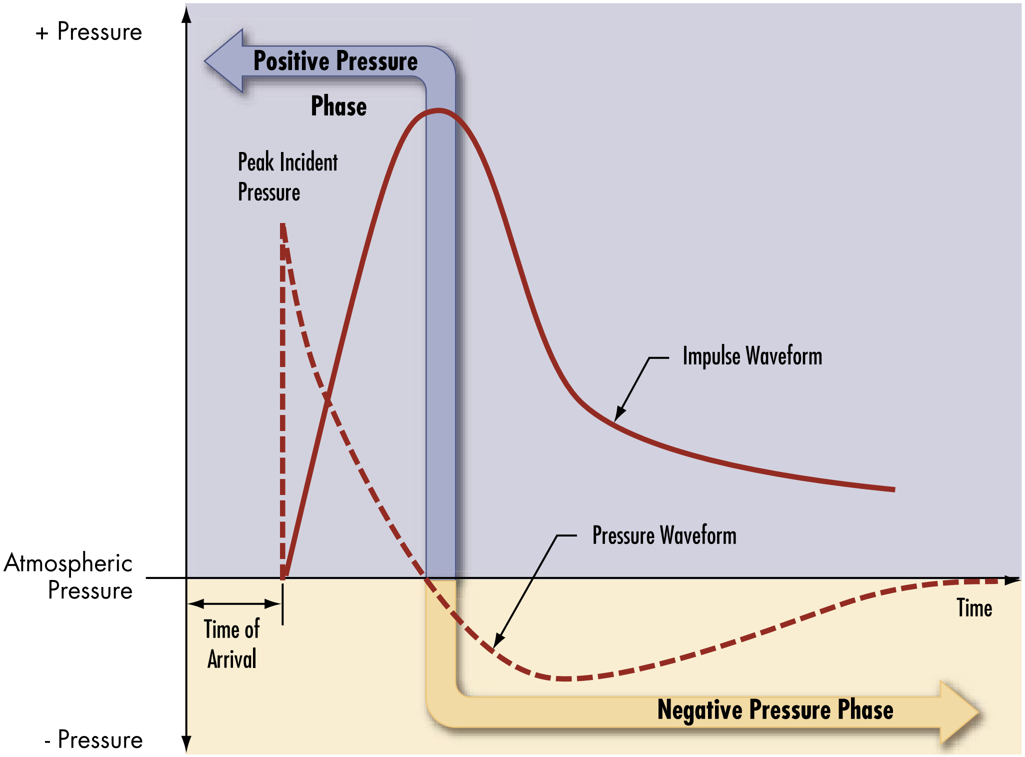


Figure 4-3 Typical impulse waveform

- Location of the detonation relative to the structure
- Reinforcement of the pressure pulse through its interaction with the ground or structure (reflections)

The reflected pressure and the reflected impulse are the forces to which the building ultimately responds. These forces vary in time and space over the exposed surface of the building, depending on the location of the detonation in relation to the building. Therefore, when analyzing a structure for a specific blast event, care should be taken to identify the worst case explosive detonation location.

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 incident pressure to be in excess of 100 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. In an urban setting, however, reflections off surrounding buildings can increase damages to the opposite side.

- 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. A discussion of progressive collapse can be found in Chapter 3.

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 4-4).

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

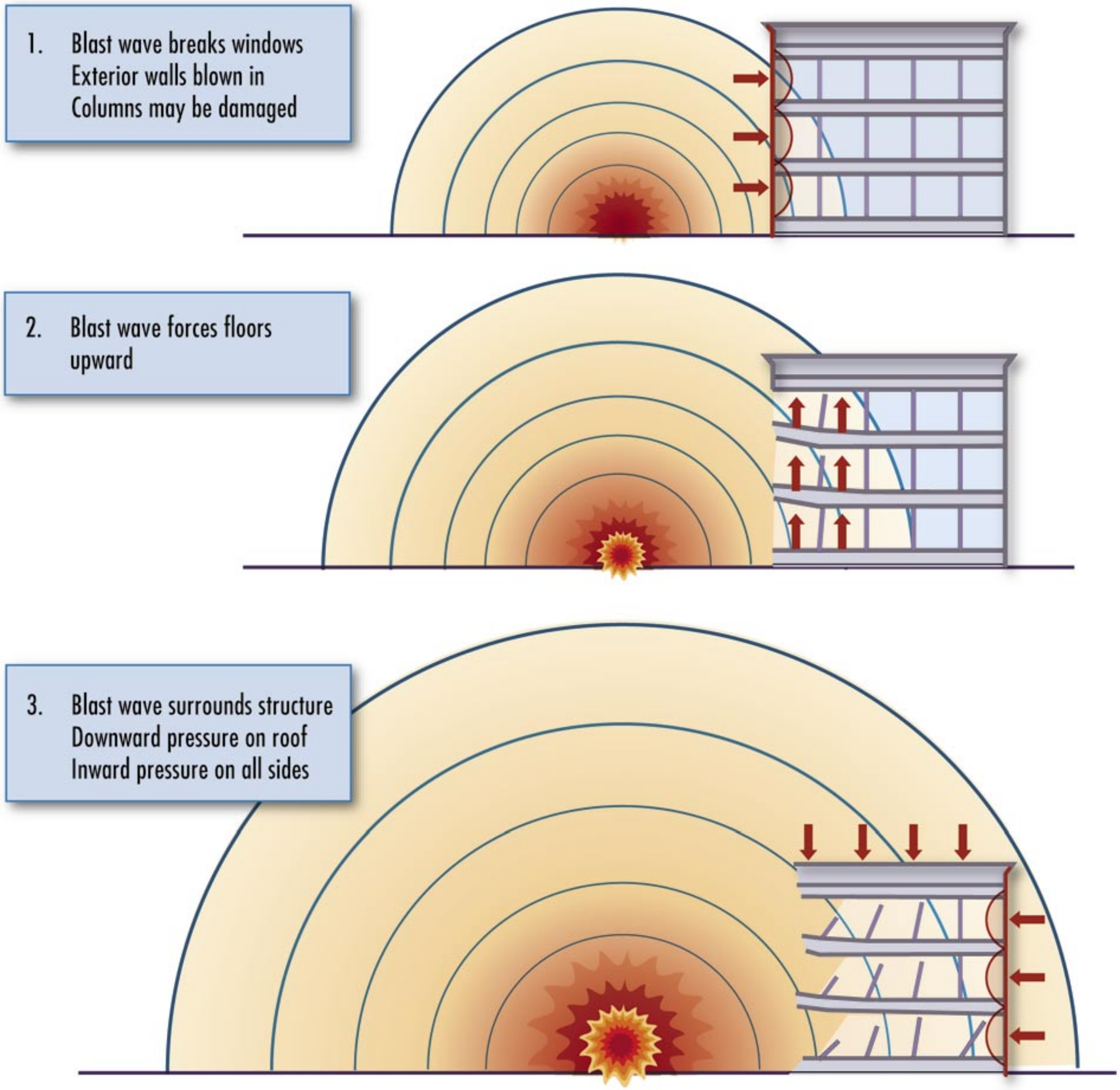


Figure 4-4 Blast pressure effects on a structure

SOURCE: NAVAL FACILITIES ENGINEERING SERVICE CENTER, *USER'S GUIDE ON PROTECTION AGAINST TERRORIST VEHICLE BOMBS,* MAY 1998

of the timing of events, the building is engulfed by the shock wave 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.

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 Injuries

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 Murrah Federal 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 minimizing 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 the DoD has five levels, they have established four levels of protection.

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.<br>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.<br>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.<br>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. |

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

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.

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

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

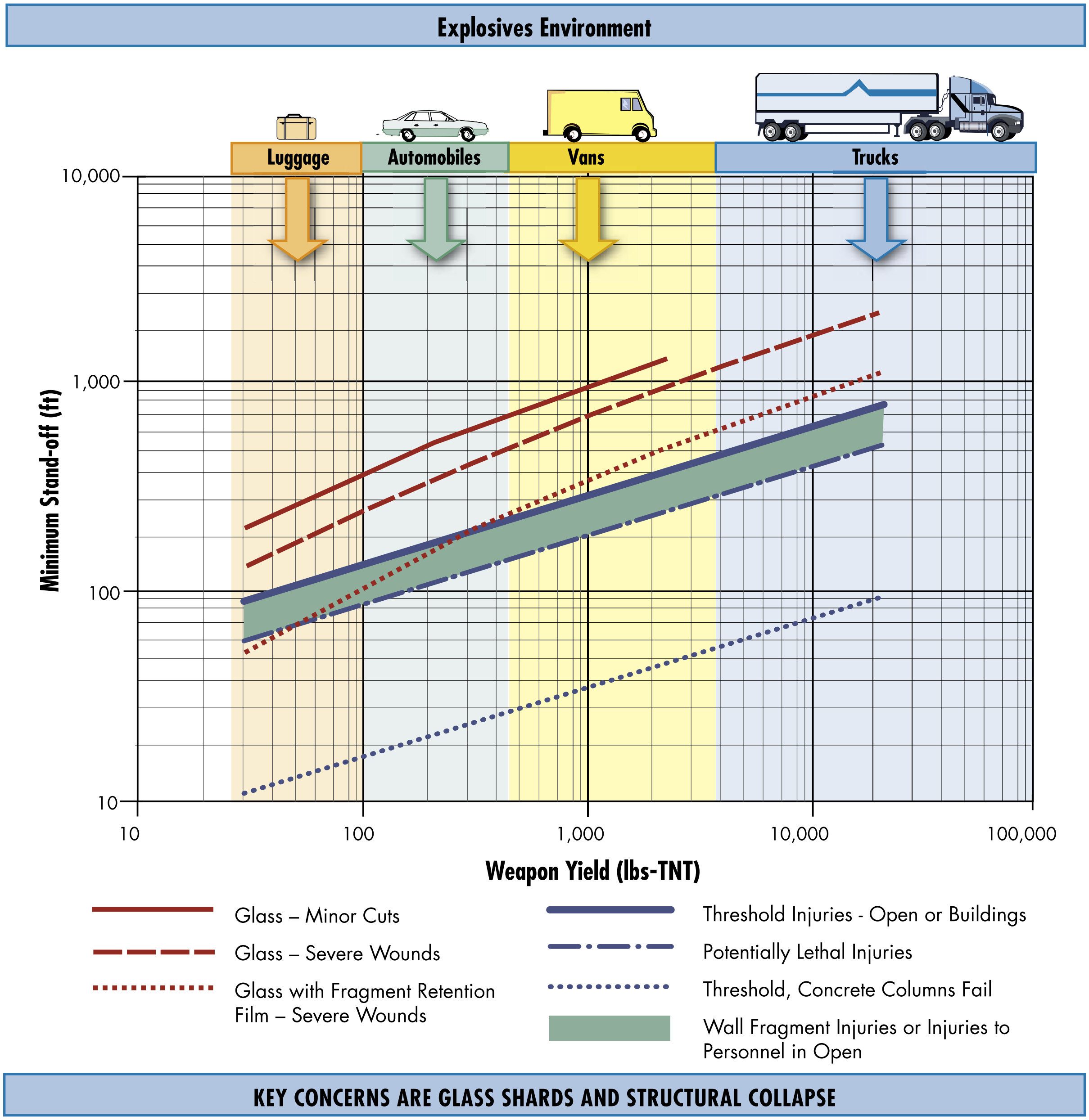
| Level of Protection | Incident Pressure (psi) |
|---|---|
| High | 1.1 |
| Medium | 1.8 |
| Low | 2.3 |

Figure 4-5 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, after the explosive weight is converted to TNT equivalence.

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. Given an explosive weight and a stand-off distance, Figure 4-5 can be used to predict damage for nominal building construction.

Figures 4-6 and 4-7 show blast effects predictions for a building based on a typical car bomb and a typical large truck bomb detonated in the

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.



SOURCE: DEFENSE THREAT REDUCTION AGENCY

Figure 4-5 Explosives environments - blast range to effects

building's parking lot, respectively. A computer-based Geographic Information System (GIS) was used to analyze the building'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 building structure. The results are shown in Figures 4-6 and 4-7.

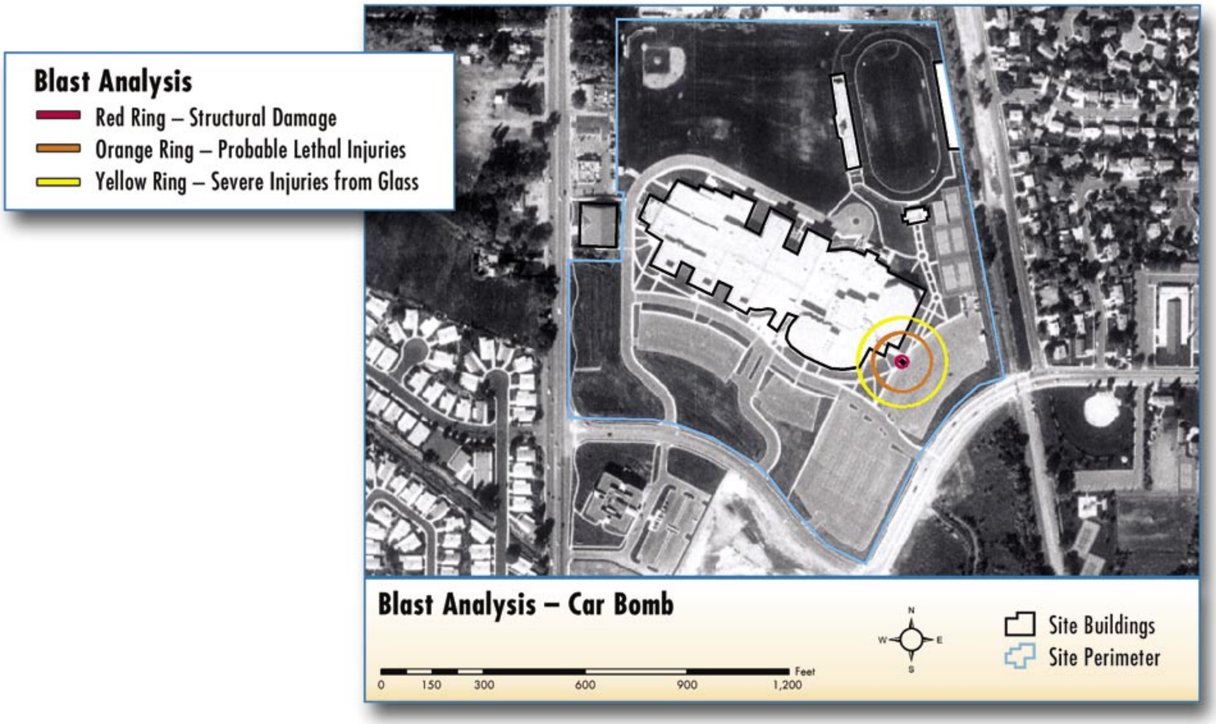


Figure 4- 6 Blast analysis of a building for a typical car bomb detonated in the building's parking lot

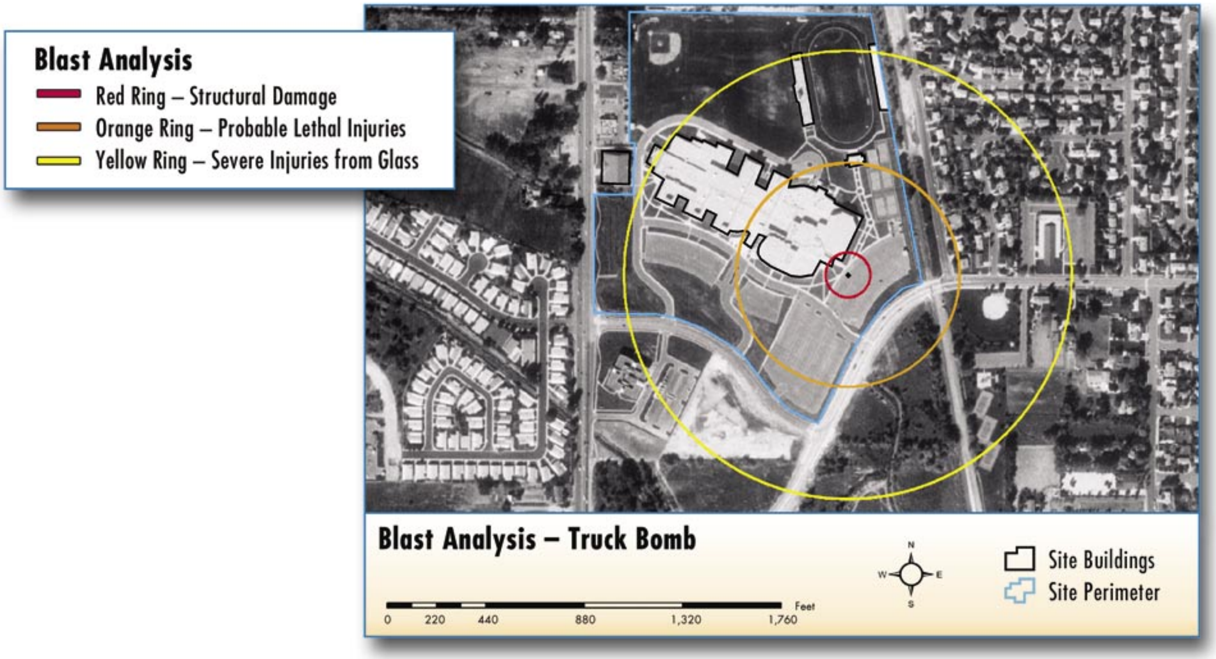


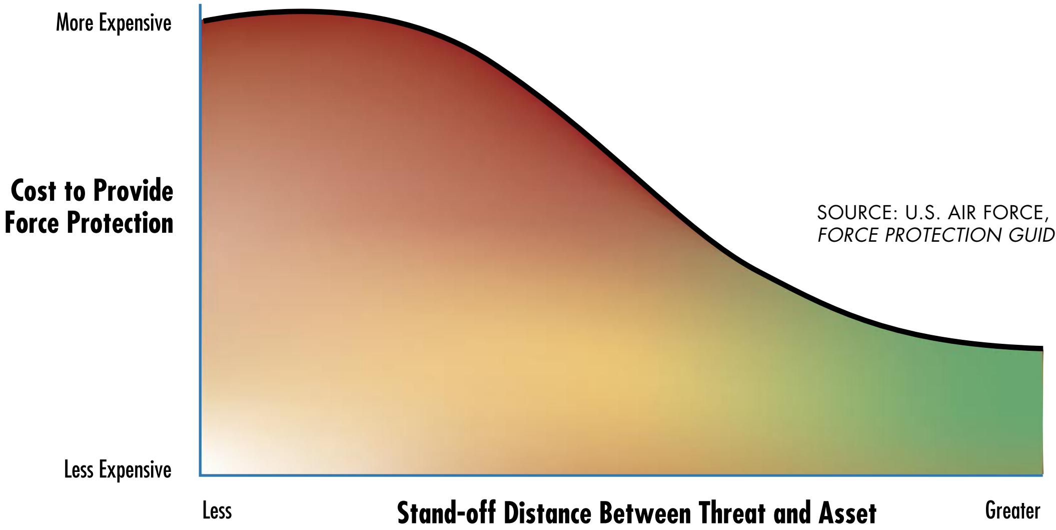
Figure 4-7 Blast analysis of a building for a typical large truck bomb detonated in the building's parking lot

The red ring indicates the area in which structural collapse 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.

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 in 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 4-8. However, increasing stand-off also requires more land and more perimeter to secure with barriers, resulting in an increased



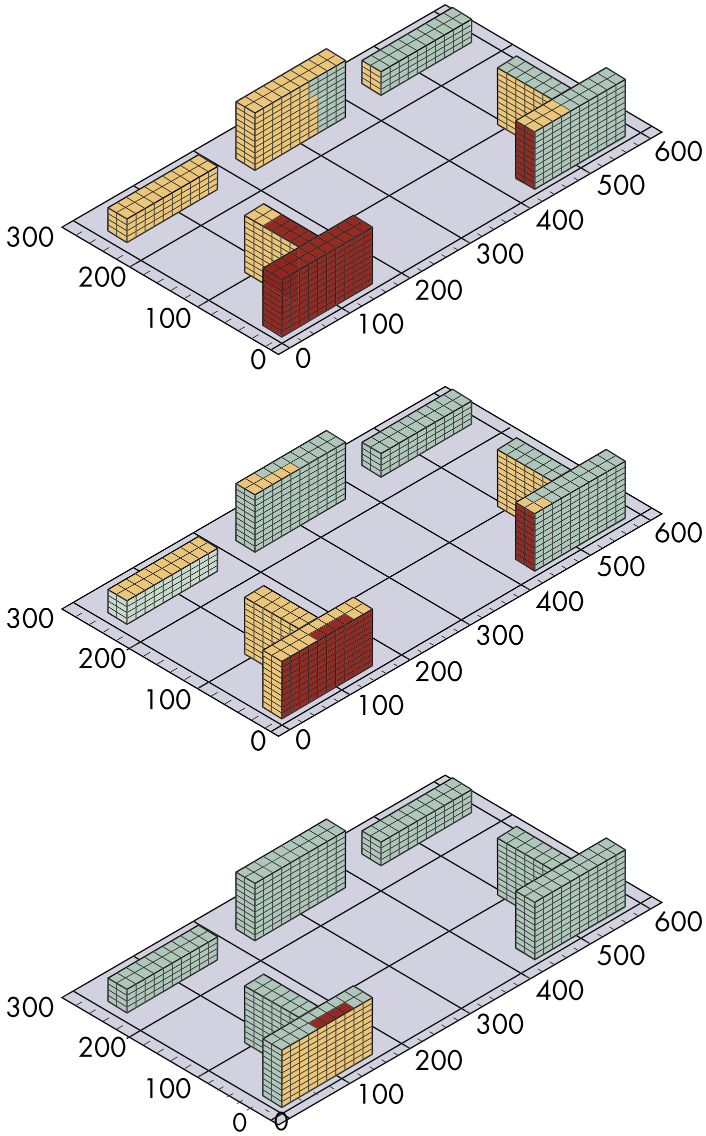
SOURCE: U.S. AIR FORCE, *INSTALLATION FORCE PROTECTION GUIDE*

Figure 4-8 Relationship of cost to stand-off distance hardening necessary to provide the required level of protection decreases. Figure 4-9 shows how the impact of a blast will decrease as the stand-off distance increases, as indicated in the blast analysis of the Khobar Towers incident. Increasing the stand-off distance from 80 to 400 feet would have significantly limited the damage to the building and hazard to occupants, the magnitude of which is shown as the yellow and red areas in Figure 4-9. Additional concepts of stand-off distance are discussed in Section 2.3.

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 Unified Facilities Criteria – DoD Minimum Antiterrorism Standards for Buildings, UFC 4-010-01, 31 July 2002).



**Detonation at 80 feet from Building 131**

This is the actual stand-off that was provided at the Khobar Towers Complex

**Detonation at 170 feet from Building 131**

This is the minimum stand-off recommended by FM5-114 Engineer Operations Short of War

**Detonation at 400 feet from Building 131**

This stand-off distance would have prevented serious damage and reduced the extent of casualties

| COLOR | DAMAGE DESCRIPTION | HAZARD TO OCCUPANTS |
|---|---|---|
| **RED** | Very severe damage, possible collapse | Very high hazard, widespread death and serious injury likely |
| **YELLOW** | Very unrepairable structural dmage | High hazard, death and serious injury possible |
| **GREEN** | Moderate Repairable structural dmage | Medium hazard, limited casualties and injury possible |

SOURCE: U.S. AIR FORCE, *INSTALLATION FORCE PROTECTION GUIDE*

Figure 4-9 Stand-off distance and its relationship to blast impact as modeled on the Khobar Towers site

The GSA and ISC Security Criteria do not require or mandate specific stand-off distances. Rather, they provide protection performance criteria. In order to economically meet these performance standards, they present recommended stand-off distances for vehicles that are parked on adjacent properties and for vehicles that are parked on the building site (see *GSA Security Criteria, Draft Revision*, October 8, 1997, and *ISC Security Design Criteria for New Federal Office Buildings and Major Modernization Projects*, May 28, 2001).

Site and layout design guidance as well as specific mitigation measures to enhance stand-off and enhance protection from explosive blast are discussed in Chapter 2.

## 4.3 PREDICTING BLAST EFFECTS

### 4.3.1 Blast Load Predictions

The first step in predicting blast effects on a building is to predict blast loads on the structure. For a detonation that is exterior to a building, it is the blast pressure pulse that causes damage to the building. Because the pressure pulse varies based on stand-off distance, angle of incidence, and reflected pressure over the exterior of the building, the blast load prediction should be performed at multiple threat locations; however, worse case conditions are normally used for decision-making.

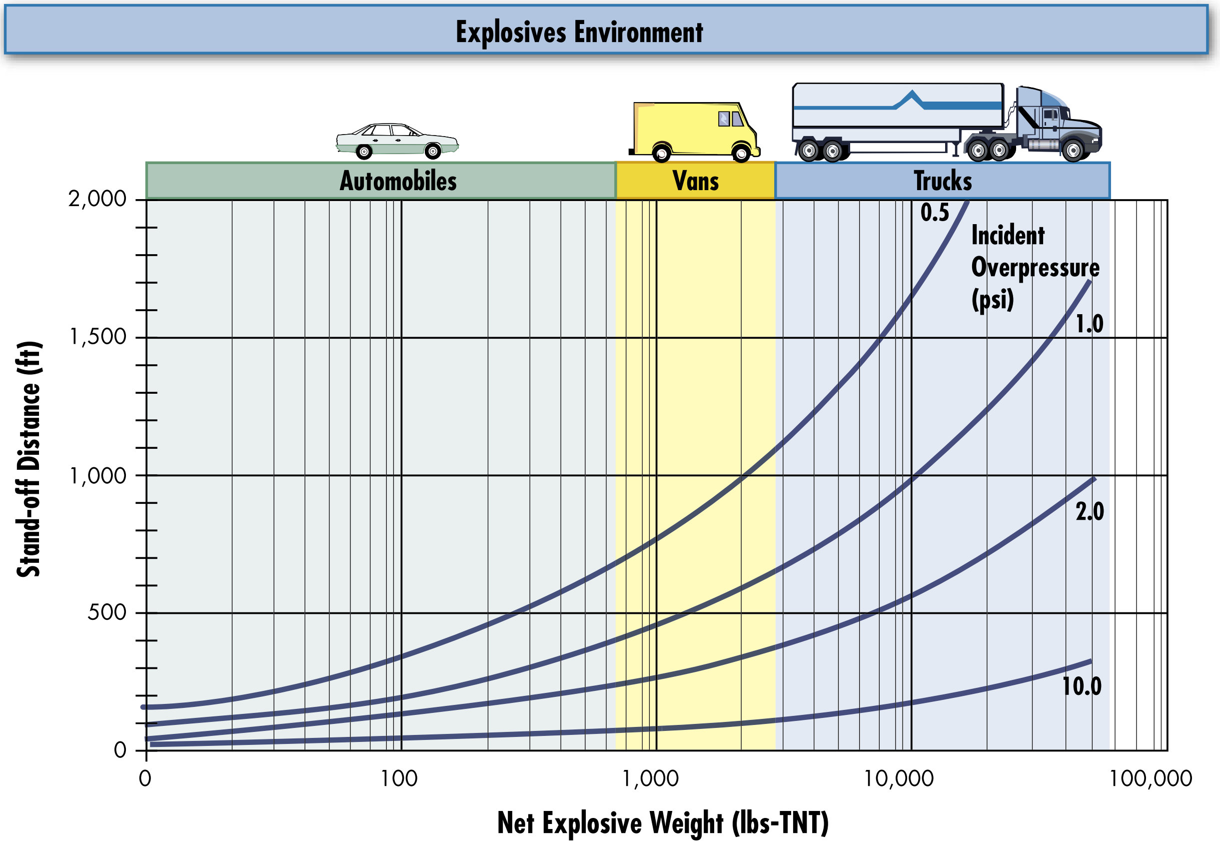
For complex structures requiring refined estimates of blast load, blast consultants may use sophisticated methods such as Computational Fluid Dynamics (CFD) computer programs to predict blast loads. These complex programs require special equipment and training to run.

In most cases, especially for design purposes, more simplified methods may be used by blast consultants to predict blast loads. The overpressure is assumed to instantaneously rise to its peak value and decay linearly to zero in a time known as the duration time. In order to obtain the blast load, a number of different tools can be used. Tables of pre-determined values may be used (see *GSA Security Reference Manual: Part 3 – Blast Design & Assess-*

*ment 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 4-10 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



SOURCE: U.S. AIR FORCE, *INSTALLATION FORCE PROTECTION GUIDE*

Figure 4-10 Incident overpressure measured in pounds per square inch, as a function of stand-off distance and net explosive weight (pounds-TNT)

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

other data, the degree of damage that the various components of a building might receive can be estimated. The vehicle icons in Figures 4-5 and 4-10 indicate the relative size of the vehicles that might be used to transport various quantities of explosives.

### 4.3.2 Blast Effects Predictions

After the blast load has been predicted, damage levels may be evaluated by explosive testing, engineering analysis, or both. Explosive testing is actively conducted by Federal Government agencies such as the Defense Threat Reduction Agency, DOS, and GSA. Manufacturers of innovative products also conduct explosive test programs to verify the effectiveness of their products.

Often, testing is too expensive an option for the design community and an engineering analysis is performed instead. To accurately represent the response of an explosive event, the analysis needs to be time dependent and account for non-linear behavior.

Non-linear dynamic analysis techniques are similar to those currently used in advanced seismic analysis. Analytical models range from equivalent single-degree-of-freedom (SDOF) models to finite element (FEM) representation. In either case, numerical computation requires adequate resolution in space and time to account for the high-intensity, short-duration loading and non-linear response. The main problems are the selection of the model, the appropriate failure modes, and, finally, the interpretation of the results for structural design details. Whenever possible, results are checked against data from tests and experiments on similar structures and loadings. Available computer programs include:

- AT Planner (U.S. Army Engineer Research and Development Center)
- BEEM (Technical Support Working Group)
- BLASTFX (Federal Aviation Administration)

Components such as beams, slabs, or walls can often be modeled by a SDOF system. The response can be found by using the charts developed by Biggs and military handbooks. For more complex elements, the engineer must resort to numerical time integration techniques. The time and cost of the analysis cannot be ignored in choosing analytical procedures. SDOF models are suitable for numerical analysis on PCs and micro-computers, but the most sophisticated FEM systems (with non-linear material models and options for explicit modeling of reinforcing bars) may have to be carried out on mainframes. Because the design analysis process is a sequence of iteration, the cost of analysis must be justified in terms of benefits to the project and increased confidence in the reliability of the results. In some cases, an SDOF approach will be used for the preliminary design and a more sophisticated approach, using finite elements, will be used for the final design.

Table 4-3 provides estimates of incident pressures at which damage may occur.

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 |

SOURCE: *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

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