SAFE ROOMS WITHIN SCHOOLS 6

This chapter is a work in progress and will be superceded by a future FEMA publication (FEMA 442) that will have expanded guidance on the subject of safe rooms. It is intended as a standalone description of the concept of safe rooms within schools that will resist CBR and blast threats and to provide school board members and decision-makers with the basic components of a protective system.

It is important to note that the probability of either a CBR or terrorist explosive event occurring in the United States is small. This is evidenced by the relatively few domestic buildings that have been targeted by intentional CBR or explosive events compared to the vast number of buildings that might be considered vulnerable. To date, two incidents of biological terrorism have been recorded and acknowledged to have had significant impacts on coincident populations in the United States: the 2001 anthrax mailings and the 1984 contamination of restaurants with Salmonella bacteria. If a localized CBR event were to occur, the potential for contamination to spread and cause collateral illnesses and fatalities up to 4 or more kilometers (approximately 2½ miles) from the target site would be likely. Unpredictable meteorological conditions would play a key role in the spread of such CBR contamination. Similarly, if an explosive event were to occur, there would be a significant potential for injuries resulting from debris impact and structural collapse. Therefore, in consideration of the proximity of some schools with respect to higher profile potential targets in the United States, school board members and administrators may determine that their select facilities require the design and construction of safe rooms. Because there are so many different types of school buildings, with so many different types of construction and materials, it is not possible to relate all the following issues to specific building types; nevertheless, an attempt was made to relate the relevant threats and the general principles of protective design to the development of safe rooms within schools.

This chapter discusses:

- The different types of hazards
- The general means by which these hazards might be addressed
- The protective methods that may be effective
- The level of effectiveness that may be achieved
- The information from which decision-makers can estimate the cost for providing different levels of protection

6.1 TYPES OF CBR HAZARDS

Chemical contaminants of concern are the chemical warfare agents (CWAs) and toxic industrial chemicals (TICs). Key attributes of CWAs and TICs are their toxicity, volatility, and availability. The most toxic CWAs are the nerve agent liquids, which include VX with high toxicity and low volatility, and Sarin with high toxicity and moderate volatility. The measured volatility of a chemical represents the ease with which the quantity of liquid chemical leaves the liquid state and becomes a gas in equilibrium with its volumetric surroundings. So, an occupant of a room where Sarin liquid is naturally evaporating is at much greater risk than the same individual being in the same room with the same or (to a degree greater) quantity of a naturally evaporating VX agent (see Appendix C). The lethality of VX exceeds the lethality of Sarin by dose, but Sarin is much more volatile than VX.

A ranking of 49 TICs with regard to their threat when used against buildings applies three factors (availability, toxicity, and delivery system) on a scale of 1 to 5, with the highest number indicating the greatest hazard. About half of the TICs considered "threat agents" are gases at standard conditions and must be transported in pressurized cylinders. The military copper-silver-zinc-molybdenum-triethylenediamine (ASZM-TEDA) carbon is effective in filtering 22 of these 49 TICs, has marginal performance against 9 TICs, and poor performance against 18 TICs. The military ASZM-TEDA carbon is a special sub-grade of bound with pitch-low (BPL) activated carbon, impregnated with salts of copper, silver, zinc, and molybdenum, and with triethylenediamine (TEDA) to enhance the carbons adsorption characteristics.

6.1.1 Toxic Industrial Chemicals

Though of lower toxicity than nerve agents, TICs are widely available, and some can be easily obtained or produced without sophisticated equipment. Among the hundreds of TICs produced worldwide are several that have been used as CWAs (e.g., arsine, chlorine, hydrogen cyanide, phosgene, hydrogen sulfide, acrolein, and cyanogen chloride). Those that have been used in warfare are considered second-rate CWAs because their toxicity and vapor pressure make them less effective than other agents for open-air battlefield use.

6.1.2 Incapacitating and Tear-producing Agents

Although incapacitating and tear-producing agents are considered non-lethal, indoor releases can, under certain conditions, produce lethal concentrations. In addition to the tear-producing agents, there are commercially available agents containing oleoresin capsicum (OC), the natural oil of chili peppers. The malicious or accidental release of pepper spray has caused many disruptive incidents in recent years. In contact with the eyes, nose, or mouth, OC causes immediate pain and inflammation. Inhaled, its aerosol causes choking and gasping for breath. Of low vapor pressure, OC is easily filtered.

6.1.3 Biological Agents

Biological agents include bacteria, viruses, and rickettsia. Toxins, which are poisons of biological origin and not living organisms, are sometimes grouped with biological agents and sometimes with chemical agents. Although there are hundreds of microorganisms that could be used as biological agents, the likely number is much smaller when the agents' effectiveness, reliability, availability, ease of manufacture, and stability in storage and dissemination are considered. When disseminated as aerosols, biological agents are most effective in the size range of 1 to 5 microns, because they can remain suspended for long periods. Smaller particles are less likely to survive as aerosols, and larger particles settle rapidly, making them less likely to enter the

HEPA filters were developed during World War II by the Atomic Energy Commission to remove radioactive dust particles from research spaces. Today, HEPA filters are used for various applications, including nuclear contamination, asbestos abatement, surgical facilities, tuberculosis wards, clean rooms, computer rooms, and other critical areas. A HEPA filter is 99.97 percent efficient in capturing particles 0.3 micron in diameter. HEPA filters are top of the line particulate filters. Although they are very good at filtering particles, they are also expensive to operate because they cause large drops in pressure. Therefore, they are generally only used in "high end" applications such as those mentioned above. HEPA filters are standard components with high-efficiency gas adsorber (HEGA) systems. These military adsorbers cost approximately $4.50 per cubic feet per minute (cfm), and their expected service life is 3 years, although service life varies with the air quality of the region and the moisture to which the filters are exposed over time. Use of only HEPA filters in a makeup-air unit would provide a high level of protection from biological agents, radiological agents, solid aerosols such as tear gas, and liquid aerosols of low vapor pressure.

lungs. The settling time in still air for an anthrax spore (1 micron by 0.7 micron in size) is approximately ½ foot per hour. Particles of this size are readily filtered from an air stream with high-efficiency particulate air (HEPA) filters. Toxins, which may be in crystalline or liquid form, are also filterable with HEPA when disseminated as aerosols.

6.1.4 Radiological Agents

Radiological agents are radioactive materials. Explosive release is the most likely means of disseminating such agents in a terrorist attack (e.g., a "dirty bomb" consisting of radioactive material packaged with a conventional explosive). The likely radioactive ingredients are those used for industrial and medical purposes (e.g., isotopes of cesium, cobalt, and iridium). They are commonly found in hospitals and labs, often with few safeguards. Given the availability of nuclear reactors for research or energy production by universities, research facilities, or private industries, the threat associated with radiological materials is significant. Radiological contaminants are very persistent, in that their decay rate is extremely slow. Unlike chemical or biological agents, decontamination involves only removal, not neutralization. Radiological aerosols present a health hazard if ingested or inhaled, but are easily filtered from an air stream with HEPA filters.

6.2 MOST LIKELY DELIVERY METHODS FOR CBR AGENTS

For purpose of vulnerability assessments, delivery methods are divided into four types of releases: internal, external proximate, remote, and remote with forewarning.

6.2.1 Internal Release

This involves transporting a container of agent into a building and releasing the contents manually, automatically, or remotely. Such a device may rely simply upon natural evaporation (as in the Tokyo subway Sarin attack), with the rate of evaporation proportional to the surface area that develops as liquid agent spills from its container. Aerosolization may occur with movement of an open package or letter containing a biological agent. A sprayer powered by batteries or compressed air can produce an effective dose of an agent quite rapidly. An agent can be released in any area served by return ducts/plenums or in a mechanical room, with dissemination through an air-handling unit. Biological agents can also be placed into certain types of humidifier systems.

6.2.2 External Proximate Release

This involves introducing an agent or a dissemination device from outside the building directly through a penetration in the building shell, such as a fresh-air intake. Vulnerability to this type of release is highest when air intakes are at accessible, unsecured locations at ground level. Agents can also be delivered through other penetrations, but potential effectiveness is less in the absence of a driving force (a fan) to introduce and distribute air within the building. A documented example of an attack through a ground-level penetration is the release of a toxic industrial gas from a pressurized cylinder through a dryer vent. External proximate release also includes forcing open or breaking windows and doors to introduce agents from pressurized cylinders or tossing a grenade or container of an agent into the building.

6.2.3 Remote Release

If directed at a specific facility, this type of attack involves a plume, puff, or line source generated so that the wind carries the agent to the target building; the facility may be the target or collaterally in the direction of the attack. The most efficient type of remote attack is a directed-plume attack with a ground-level source placed upwind of a building's fresh-air intakes or open windows. A ground-level, directed-plume attack was conducted with the nerve agent Sarin from a distance of 60 yards in Matsumoto, Japan, in 1994, killing 7 and injuring 264 in a zone 500 yards deep and 100 yards wide. A remote attack can also involve an aerial release. Release from an aircraft is much less likely to affect a specific, targeted building, however, because the vertical rate of transport, governed by settling time and atmospheric stability, is extremely difficult to judge.

6.2.4 Remote Release with Forewarning

This type of attack differs from other remote releases because protective actions other than those for no-warning attacks can be applied. This type involves warning in the form of an explosion or an event such as an accidental or intentional release of an agent from a chemical transport or storage tank. Scenarios involving forewarning include sabotage of toxic industrial storage tanks/ trucks, transport accidents, fires, or the impending release of a chemical agent from a point upwind of the building. Quantities of agent that could be released from a single 3,000-gallon tanker truck are approximately 34,000 pounds for phosgene, 35,000 pounds for chlorine, and 17,000 pounds for hydrogen cyanide.

Scenarios

Aside from the recent attacks with mail-delivered anthrax of the past year, no CBR terrorist attacks have occurred on U.S. Federal Government facilities; therefore, based on precedence, the probability of such attacks is very low. Without intelligence information indicating that a specific group or person possesses plans, knowledge, resources, and motivation to carry out a CBR attack, the likelihood of such an attack can be estimated only by factors unrelated to specific groups. These factors relate to the target, environmental conditions, and difficulty of attack. Target factors include the value or symbolism of the target, recognizability, and appearance of vulnerability. Factors that relate to the difficulty of attack and conditions are: availability of the agent, complexity of the delivery method/system, effect of weather, standoff distance, and deterrence (risk to the attacker, likelihood of being observed/thwarted).

There is no justification on the basis of precedence to identify a school as a probable target for a direct terrorist attack. However, a school may be located in the vicinity of other U.S. government buildings or other iconic properties that may be more recognizable and of greater perceived target value. The more likely scenario for such schools, therefore, is one of collateral effects resulting from a remote release. General scenarios for remote release are presented below, followed by internal/proximate scenarios that would involve directly targeting a building.

6.3 VULNERABILITY TO REMOTE CBR RELEASE

In the absence of a secure perimeter around the building (see Section 2.4) and a real-time detection system, vulnerability to a remote release is determined by: 1) the efficiency of the school building's filtration system in removing aerosols and gases, 2) the unfiltered component of air exchange, and 3) the configuration of the school building and elevation of air intakes. These vulnerabilities can be characterized as follows.

Against an external hazard, the level of protection provided by a school building with a filtration system is defined in terms of protection factor (i.e., the dose [concentration integrated over time] of an agent outside divided by the resulting dose of agent inside). If all makeup air passes through filters, the protection factor equals the inverse of the penetration factor of the filter (1 minus the filter removal efficiency).

- **Efficiency of gas filtration.** Generally, if adsorbers are found in buildings, they are for the purpose of improving indoor air quality by removing both outdoor and indoor air pollutants, particularly corrosive gases such as sulfur dioxide, nitrogen dioxide, and ozone, and are used where appropriate for protecting against the deleterious effects of these gases. Although not intended for protecting people from toxic chemical agents, these gas adsorbers do reduce the vulnerability to an attack with certain chemical agents.

  With a 1-inch bed thickness of coarse (4x6 mesh) sorbent granules and a short residence time of these indoor air quality filters, the efficiency is about 99 percent initially, and it diminishes with time in service, typically to about 25 percent in a year. There is also an initial bypass of roughly 1 percent through the bed and additional bypasses among filter modules' holding frames. The bypasses may increase with time in service, dropping the net efficiency below the initial level. This compares with an efficiency of greater than 99.999 percent for gas adsorbers designed for protection of people in military applications. Removal efficiency for these indoor air quality adsorbers is relatively low and uncertain for some of the threat agents (the capacity for arsine is low, for example). Thus, the efficiency and capacity are highly variable. Manufacturers provide surveillance testing to determine when to change filters and recommend that they be changed when reactive capacity has dropped to 25 percent of the initial value. The typical service life for single stage, 1-inch beds is approximately 1 year.

- **Particulate filtration.** Significant particulate filtration can be accomplished by using a 35-percent pre-filter and a 95-percent filter in series. The efficiency of this filter train is in the range of 95 to 99 percent for 1-micron particles in the new condition, and this efficiency increases as the filters load.

- **Unfiltered air exchange.** Typical of schools, a substantial portion of the air exchanged between indoors and outdoors may not pass through the filters of any air-handling units. When this occurs, the level of protection the building structure provides is, therefore, governed not by the efficiency of the filters but rather by that portion of makeup air bypassing the filters. There are several paths by which air exchange is driven by fans, buoyancy, and/or wind pressures. They include operable windows; doorways with flows driven by buoyancy, particularly in summer and winter when indoor-outdoor temperature differentials are highest; and unintentional openings in the building shell. When internal resistance is minimal, less dense (buoyant) warm air rises and flows out of a school building near its top in winter, drawing in cool air at the lower levels. Conversely, in summer, cool air falls and flows out of the building's base. The buoyancy effect tends to be less pronounced in spring and fall because of smaller indoor and outdoor temperature differences. With the standard draw-through configuration of the air-handling units, leakage paths at the access doors and panels are subject to inward pressure; these leakage paths increase as the gaskets age. Typically, access doors also fail to seal well with filter frames, allowing bypass that increases with age.

- **Typical protection factors achievable**. In terms of protection factor, protection against aerosols (biological/radiological agents and others such as tear gas) provided by the best (standard) filtration systems available in air-handling units is substantial, but relatively low (in the range of approximately 5 to 50). Protection factor is a ratio of dose (concentration integrated over time) of an agent outside divided by the resulting dose of agent inside a building). This level of protection is comparable to that achievable with sheltering in place or an active detection-based system that responds by de-energizing fans and closing dampers. The higher value in this range is estimated by taking the inverse of the penetration factor for 1-micron particles through the filters, including an initial bypass of approximately 1 percent. The lower value in the protection-factor range is estimated for both particulate and gas filters by using 20 percent as an estimate of the unfiltered air exchange; the inverse of the penetration factor (0.2) is 5.

With an indoor air quality filter unit having a gas adsorber, the protection factor for gases can be as high as 50, but only when filters are new and only with gas adsorbers. The protection drops to a low value as the filter efficiency decreases with time in service. This may be less than 2 if the efficiency drops below 50 percent after 1 year in service. The protection factor against gases is also reduced by the portion of outside air (which could be at least 80 percent) that does not flow through gas adsorbers. With a penetration of 80 percent, the protection factor for gases for the whole building is less than 2.

Summary: Vulnerability to Remote Release

A typical building would have high vulnerability to a remote release of aerosols (biological and radiological agents) and a high vulnerability to a remote release of gases (chemical agents). The basis for this rating is:

- Estimated protection factors are in the range of 5 to 50 for aerosols, based on a substantial volume of unfiltered air exchange.
- Use of gas adsorbers is atypical of building air-handling ventilation systems.
- Outside air intakes in building construction are often located near ground level, making them especially vulnerable.

Vulnerability can be reduced by:

- Application of gas adsorbers to all air-handling units
- Employing particulate filters of higher efficiency (e.g., 95 percent) and low bypass

6.4 VULNERABILITY TO REMOTE CBR RELEASE WITH FOREWARNING

This type of attack involves release of agent by explosion or rapid release from a tanker truck, rail car, or fixed storage tank. The potential for this type of attack is higher when the facility is near rail lines, public roads with truck traffic, or storage tanks of toxic chemicals. This type of attack may also involve an explosive release of a radiological agent (i.e., a "dirty bomb" attack at a distance from the building great enough to allow for protective actions to be taken before wind carries the agent to the building).

The criterion for this aspect of vulnerability is the ability to rapidly assume a sheltering-in-place posture (see Section 5.2). The main requirements are plans/procedures for sheltering, controls to rapidly turn off all fans, and a communications or public address system to facilitate closing of doors and keeping them closed while an outdoor hazard is present or imminent. Protection factors vary, diminishing with time of exposure; however, scenarios of explosive release under most conditions would present a relatively short exposure to the school building.

Summary: Vulnerability to Remote CBR Release With Forewarning

A typical school building would have high vulnerability to a remote release with forewarning. The basis for this rating is:

- ❍ Schools should develop plans/procedures for sheltering and rapid deactivation of all fans and closing of doors and windows.
- ❍ Schools have limited filtration capabilities for gases and aerosols; therefore, the vulnerability to a remote release with forewarning is aproximately the same as the vulnerability to a remote release without forewarning.

Vulnerability can be reduced by:

- ❍ Developing an emergency plan for sheltering in place that includes rapidly de-energizing all fans and closing doors and windows.

6.5 VULNERABILITY TO INTERNAL CBR RELEASE

This is a remote possibility owing to the nature and likelihood of other vandalism and that actual targeting of a school has no historical precedence. Nevertheless, internal releases involve covert entry or covert introduction of agents in containers. Vulnerability to internal release is, therefore, determined principally by physical security measures in place. Containers of agents may be hand-carried or delivered in mail, supplies, or equipment. Other factors affecting this vulnerability are internal (recirculation) filtration and how well entry zones where any screening takes place are isolated architecturally and mechanically.

The basis for preventing covert introduction of agents is access control and entry screening. Use of the X-ray machine for hand-carried items facilitates the detection of containers large enough to hold hazardous quantities of chemical agents; however, it requires specific operating procedures for doing so, and it may not be effective in detecting containers of hazardous quantities of biological agents. Obviously, such procedures are not recommended for schools without provocation (i.e., an actual threat) because of cost.

6.6 VULNERABILITY TO EXTERNAL PROXIMATE CBR RELEASE

Vulnerability to external proximate release is determined mainly by the accessibility of outside air intakes to covert introduction of agent or agent-dissemination device. Unless air intakes are relocated at a higher elevation, this vulnerability would remain high.

The three strategies for protecting a school building from airborne hazards originating outdoors are air filtration, controlling air exchange, and exclusion by physical security. Options presented in this chapter focus on air filtration; however, enhanced filtration techniques discussed earlier would be applied most economically in schools to a selected safe room, such as a school gymnasium or auditorium. Without a secure exclusion zone around the school building, physical security measures are limited to those described above for external proximate release and internal release.

Controlling air exchange is most commonly employed with human detection and warning (i.e., sheltering in place). It can also be applied with automatic, real-time detection equipment, but with very limited effectiveness. Few agents among the full spectrum of threat agents can be detected with accuracy in real time. Protection factors vary with response time and, even with instantaneous response, protection factors are no greater than the maximum protection factors achievable with sheltering in place. As the response time increases, protection factors diminish. With current technology, response times are longest for biological agent detection. The response time for presumptive identification by a detector such as the Joint Biological Point Detection System is approximately 30 minutes and far exceeds the response time needed for effective use of sheltering in place. A biological detection system would not, therefore, prevent the contamination of a particular building.

- **Criteria for protective performance.** All of the following discussion represents extreme measures applied to high-risk, high-security assets or, in general, to lesser degrees, safe rooms, and perhaps to would-be safe rooms for schools. There is no standard requirement for protection factors. U.S. military systems are designed to achieve protection factors greater than 10,000. The criterion applied to military masks and collective protection shelters is 6,667, which is based upon specific levels for chemical agents on the battlefield and for threshold effects of the chemical agents on soldiers. There is no criterion for biological or radiological agents based upon concentrations and doses likely to be developed in an attack on a school building; however, it would be 10,000 or greater.

To increase the protection factors to 10,000 or higher for selected envelopes requires: 1) high-efficiency filters (HEPA and HEGA) with leak-tight seals at the holding frames; 2) pressurization of the protective envelope; 3) pressurization of mechanical rooms in which air-handling units are located and return ducts not within the protective envelope; 4) adding vestibules/airlocks at entrances to protected zones where entry/exit is frequent; and 5) permanently closing windows.

The selection of a CBR safe room in a school building requires an assessment of factors contributing to infiltration (or wind penetration from the outside). To prevent infiltration through the protected envelope requires an internal pressure of approximately 50 Pascals [0.2 inch, water gauge (iwg)]. This pressure does not prevent infiltration driven by buoyancy and wind pressures under all possible conditions, but it does so under wind conditions most conducive to a (stand-off) plume attack (see Table 6-1). The level of safe room pressurization should exceed 95-99 percent of the meteorological conditions for the given school location. Note that wind does not exert a uniform pressure on a building face; the pressure varies by location on the building face and the angle of incidence. A 20 mile-per-hour (mph) wind velocity is not uncommon in the United States and, thus, a safe room pressurized to 50 Pascals would prevent infiltration from time averaged 20 mph winds.

Table 6-1: Pressures Exerted on a School Building Face by Wind

Wind Velocity* [mph]	From [Pascal]	To [Pascal]
2	0.2	0.4
4	1.0	1.7
6	2.2	3.9
8	3.9	6.9
10	6.0	10.8
15	13.5	24.4
20	24.1	43.3
25	37.6	67.7

*Time Averaged and Normal (90%) Incidence to School Building Face

There are several options for improving protection factors with filtration; they involve both the type/configuration of the filter system and the extent of the protective envelope.

- **Options for type of filter system.** Four options for a dedicated type of filtration system for a safe room include:

  - **Improving mixed-air particulate filtration of air-handling units.** Particulate filters may be upgraded to 95-percent filters, providing the potential for substantial improvement in protection against biological agent aerosols. The limit of protection factor against 1-micron particles, however, is approximately 100 with pressurization of the protective envelope and reduction of bypass at the filter frames. Reduction of bypass requires sealing and gasketing existing retainers, slide-in tracks, and access doors, and adding gaskets between filter frames in slide-in tracks. Pressurization can be achieved by rebalancing the air-handling units and controlling the flows through open doorways and windows. Among the options for improvement are to upgrade the filters to HEPA with leak-tight holding frames; with pressurization, this would increase the potential protection factor to about 10,000 for biological agents, but not for chemical agents. This option requires special holding fixtures for the filters and may require replacement of supply fans to accommodate higher pressure drop.

  - **Improving mixed-air gas filtration of the air-handling units.** An option to increase protection factors of a school building for chemical agents is to install gas adsorbers in air-handling units. This would involve adding the indoor air quality (IAQ) type adsorbers to existing air-handling units, at a cost of $0.50 per cfm. With a 1-year service life, the filter replacement costs would be $0.25 per cfm. Additional energy related operating costs would be incurred due to the pressure drop of the adsorbers (0.75 iwg). This option does not provide high efficiency against all chemical agents.

  - **Installing makeup-air units with HEGA and HEPA filters.** A makeup air unit for both gases and aerosols includes the following components in series: pre-filter, fan, HEPA filter, HEGA filter, and heating and cooling coils. The makeup-air unit provides filtered outside air to pressurize the protective envelope. It eliminates recirculation and the internally induced infiltration associated with applying a single fan for both makeup air and recirculated air. The most cost-effective HEGA filter units currently available for protection from chemical agents employ the military-standard 200-cfm radial-flow filters per MIL-PRF-51527A, “Filter Set, Gas-particulate, 200 cfm," Type II. These contain ASZM-TEDA carbon of 12x30 mesh size in 2-inch-deep beds, which removes all chemical warfare agents and a substantial number of toxic industrial chemicals. These provide removal efficiency greater than 99.999 percent throughout their service life (estimated at 3 years). HEPA filters are standard components with HEGA systems. These military adsorbers cost approximately $4.50 per cfm, and their expected service life is 3 years, although service life varies with the air quality of the region and the moisture to which the filters are exposed over time. Maintenance costs run approximately $2 per year per cfm. Maintenance also includes changing HEPA filters annually and pre-filters every 90 days. With total pressure drop of 6 iwg across the adsorber and HEPA filter, energy costs for the high-efficiency filtration run approximately $0.50 per cfm per year.

- **Installing makeup-air units with HEPA only.** Use of only HEPA in a makeup-air unit would provide a high level of protection from biological agents, radiological agents, solid aerosols such as tear gas, and liquid aerosols of low vapor pressure. High-level protection against biological aerosols is particularly beneficial because there is no capability for real-time detection of biological agents (all strategies that require biological detection are mitigation strategies involving decontamination and medical treatment). Use of HEPA only in a makeup-air unit would substantially reduce hardware costs, maintenance costs, and electrical costs of ventilation as well as the space requirements for the units. Protection at a lower level would still be provided by filtration of recirculated air with gas adsorbers in air-handling units.

6.7 RECOMMENDATIONS FOR CBR PROTECTION

The following actions are recommended for CBR protection:

- To provide a substantial level of protection against an external release of CBR agents, apply any one of the filtration options summarized above to a renovated school gymnasium or auditorium safe room.

- To protect against a remote attack with a chemical or radiological agent, plans, procedures, and training for sheltering in place should be developed. To support this protective measure, a rapid notification system (public address system) and controls for rapid deactivation of fans and closing of dampers should be defined. A guide for developing protective action plans is available in the Army Corps of Engineers draft Technical Instruction TI 853-01 *Protecting Buildings and Their Occupants from Airborne Hazards*, dated October 2001.

- To reduce vulnerability to internal release, implement security procedures specific to entry screening for containers of unknown liquids or gases being carried into the secure area. Provide training to employees on awareness of the CBR threat and the protective action plan.

6.8 SAFE ROOMS IN RESPONSE TO THE DOMESTIC EXPLOSIVE THREAT

The concept of safe rooms has been around for quite some time. Bomb shelters were used in the United Kingdom (U.K.) during World War II to protect the civilian populations against aerial attack and fall-out shelters were established in cities in the United States during the Cold War to protect against the lingering effects of a feared nuclear attack. More recently, the Israeli Defense Force (IDF) requires apartment protected spaces (APSs) or floor protected spaces (FPSs) to be constructed in every new building or to be added to existing buildings according to engineering specifications. In buildings in which no shelters exist, interior rooms may be converted to shelters by following IDF instructions. In all cases, the shelters must be accessible within 2 minutes of a warning siren. The protected spaces are intended to serve as a refuge when an attack is suspected, either through early warning or remote detection; however, the protected space is much less effective when the event takes place without warning. Two minutes and eleven seconds elapsed between the time the Ryder truck stopped in front of the Murrah Federal Building in Oklahoma City and the detonation of its explosives, but no one was alerted to the danger until the explosion occurred.[1] At Khobar Towers in Dhahran, Saudi Arabia, U.S. Air Force Security Police observers on the roof of the building overlooking the perimeter identified the attack in progress and alerted many occupants to the threat; however, evacuation was incomplete and 500 people were wounded and 19 people were killed by the explosion.[2]

The effectiveness of the safe room in protecting occupants from the effects of an explosive detonation is, therefore. highly dependent on early detection and warning. Unless the attacker notifies authorities of a bomb threat, as often occurred in the terrorist activities in Northern Ireland, the safe room can best be used after an explosion occurs in anticipation of a second attack. The 1998 bombing of the U.S. Embassy in Kenya was preceded by a small explosion that drew curious embassy employees to the windows; such a tactic, if repeated in the United States, would justify the relocation of school occupants to a safe room until school officials are able to determined that it is safe to disperse the students. To these limited objectives, the establishment of a safe room in schools may serve a useful purpose. Given the nature of the explosive threat, however, it may be more effective to provide debris mitigating protective measures for all exterior façade elements.

It is important to understand the nature of the domestic explosive threat in order to effectively plan for the protection of different

[1] The structural features of the building, including the transfer girders that spanned over the main entrances, along with the relatively short distance from the curb to the face of the building, were the most significant contributing factors to the collapse.

[2] Although the precast structure was subjected to overwhelming blast loads, which blew the front façade into the occupied spaces, the building was designed to the U.K. regulations, which have provisions for structural robustness that require precast components to be tied together.

types of facilities and particularly for the establishment of safe rooms in schools. Although the patterns of past events may not predict the future, they give valuable insight to the protection against a very low probability, but potentially high consequence event. As previously discussed, despite a wide range of terrorist events, such as CBR contamination, an explosion remains the most insidious threat, requiring the least sophisticated materials and expertise. The principal components of an explosive device can be obtained at a variety of retail outlets, without arousing suspicion. Every year, over 1,000 intentional explosive detonations are reported by the FBI Bomb Data Center. In 1998, the last year for which the compiled data were published, there were 1,225 actual incidents of unauthorized explosions in the United States.[3] The majority of these explosives were targeted against residential properties and vehicles; however, 76 explosive events were detonated at educational facilities, causing a total of $28,500 in property damage.[4] In addition to these actual events, 63 incidents involving hoax devices were investigated. By contrast, only one explosive device was detonated at a Federal Government facility, causing $1.5 million in property damage, and eight were detonated at local/state government facilities, causing $316,000 in property damage. Over 70 percent of the people involved in bombing incidents were "young offenders" and less than ½ percent were members of terrorist groups. Vandalism was the motivation in 40 percent of the intentional and accidental bombing incidents. Although two out of three attacks were perpetrated between 6 p.m. and 6 a.m., the incidents against educational facilities were more uniformly distributed throughout the day. Although each successive major domestic terrorist event exceeded the intensity of

Types of Explosive Threats

As explained in Chapter 4, the effects of an explosion primarily depend on the weight of the explosives, the type of the explosives, and the distance from the point of detonation to the protected structure. Different types of explosive materials are classified as high energy and low energy, and these different classifications greatly influence the damage potential of the detonation. High energy explosives, which efficiently convert the material's chemical energy into blast pressure, represent less than 1 percent of all explosive detonations reported by the FBI Bomb Data Center. The vast majority of the incidents involve low energy devices in which a significant portion of the explosive material is consumed by deflagration. In these cases, a large portion of the material's chemical energy is dissipated as thermal energy, which may cause fires or thermal radiation damage.

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[3] U.S. Department of Justice, Federal Bureau of Investigation, General Information Bulletin 98-1.

[4] The Bomb Data Center information does not indicate whether any of these events were preceded by a warning nor does it indicate the average weight of explosives used.

the predecessor, this is not particularly relevant to the threats to which a school structure might be subjected; if an explosive were to be detonated in or around a school building, it would most likely be a small improvised device assembled by a youth and vandalism is most likely to be the motive.

The size of the explosive that might be considered for a protective design is limited by the maximum weight that might be transported either by hand or by vehicle (for additional information, see Section 4.2). Despite the large weight of explosives that might be transported by vehicle, there have been relatively few large-scale explosive events within the United States. The 1995 explosion that collapsed portions of the Murrah Federal Building in Oklahoma City contained 4,800 pounds of ammonium nitrate and fuel oil (ANFO) and the 1993 explosion within the parking garage beneath the World Trade Center complex contained 1,200 pounds of urea nitrate. As implied by the FBI statistics, the majority of the domestic events contain significantly smaller weights of low energy explosives. The explosive that was used in the 1996 pipe bomb attack at the Olympics in Atlanta consisted of smokeless powder and was preceded by a warning that was called in 23 minutes before the detonation. Nevertheless, the protective design of structures focuses on the effects of high energy explosives and relates the different mixtures to an equivalent weight of trinitrotoluene (TNT).

As discussed in Chapter 4, the distance of the protected structure from the point of explosive detonation is commonly referred to as the stand-off distance. As the front of the shock-wave propagates away from the source of the detonation at supersonic speed, it expands into increasingly larger volumes of air, the peak incident pressure at the shock front decreases, and the duration of the pressure pulse increases. The shock front first impinges on the leading surfaces of a structure located within its path and then engulfs the entire structure. Both the intensity of peak pressure and the impulse, which considers the effect of both pressure intensity and pulse duration, affect the hazard potential of the blast loading. Other issues, such as the geometry of the waves impacting the protected structure and the reflectivity of the surroundings, will either amplify or reduce the intensity of the blast loading.

6.9 LOCATING SAFE ROOMS TO MITIGATE THREATS

The building's façade is its first real defense against the effects of a bomb and typically the weakest component that would be subjected to blast pressures. Although the response of specific glazed components[5] is a function of the dimensions, make-up, and construction techniques, the conventionally glazed portions of the façade would shatter and inflict severe wounds when subjected to a 50-pound explosive detonation at a stand-off distance on the order of 200 feet. If the glazed elements are upgraded with a fragment retention film (FRF), the same façade element may be able to withstand a 50-pound explosive detonation at a stand-off distance on the order of 70 feet. Unreinforced masonry block walls are similarly vulnerable to collapse when subjected to a 50-pound threat at a stand-off distance of 50 feet; however, if these same walls are upgraded with a debris catching system, they may be able to sustain this same intensity explosive detonation at a stand-off distance on the order of 20 feet. If the weight of explosives were increased from 50 pounds to 500 pounds, the required stand-off distances to prevent severe wounds increases to 500 feet for conventional window glazing, 200 feet for window glazing treated with a FRF, 250 feet for unreinforced masonry block walls, and 60 feet for masonry walls upgraded with a debris catching system. Based on these dimensions, it is apparent that substantial stand-off distances are required for the unprotected structure and these distances may be significantly reduced through the use of debris mitigating retrofit systems. Furthermore, because blast loads diminish with distance and geometry of wave propagation relative to the loaded surface of the building, the larger threats at larger stand-off distances are likely to damage a larger percentage of façade elements than the more localized effects of smaller threats at shorter stand-off distances. Safe rooms that may be located within the school should, therefore, be located in windowless spaces or spaces in which the window glazing was upgraded with a FRF.

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[5] Glazing refers to the glass make-up, either single pane or insulated double pane, that is used in a window system.

Vulnerability to Domestic Explosive Threat

Throughout this primer, recommendations have been provided for schools that may be considered to be at high risk with the sound knowledge that schools are not currently considered to be at risk from potential terrorist attacks. However, it is important to note that proximity of a building to a high valued or iconic facility or its proximity to an industrial facility containing volatile chemicals may influence a structure's risk to blast damage. In particular, if a school is located in close proximity to a U.S. courthouse, federal office building, or major financial institution, it may suffer collateral damage in the event the high-risk structure is the target of an explosive event. Similarly, if the school is located in close proximity to a grain elevator or industrial plant handling explosive materials, it may suffer collateral damage in the event of an accidental explosion. Although the increased vulnerability is a function of the stand-off distance and weight of explosive, large quantities of glass may fail in response to the detonation of a vehicle bomb. The risk to the protected structure is, therefore, a function of the risk of its being the intended target of an attack and the risk of being in close proximity to another structure that is the intended target of an attack. Schools in rural and suburban sites are typically sited on large parcels of land and surrounded by athletic fields and parking lots. This increases the stand-off distance from publicly traveled roadways. Schools in urban sites may be located in close proximity to prominent structures that are more likely to receive explosive threats and the stand-off distances to these threat locations may be sufficiently small to place the school building in jeopardy of significant collateral damage. School buildings that were located within several blocks of the World Trade Center were affected by the terrorist events. Urban school buildings should be evaluated on a case by case basis to determine their vulnerabilities and risks.

The history of domestic explosive events doesn't justify the inspection of hand carried parcels into school buildings. Although metal detection and parcel searches are implemented within problem districts, these are primarily for other types of weapons or controlled substances. However, if an explosive device were to be carried into a school and detonated within the building, the resulting pressures would be confined and the effects of the explosion would be amplified. The blast waves and subsequent gas pressures would seek the path of least resistance as it seeks to equilibrate with the undisturbed atmosphere. Although the pipe or parcel bomb is small compared to the weights of explosives that might be transported in a vehicle, it would inflict injuries to occupants in close proximity and within direct line of sight of the detonation or located behind conventional nonstructural partitions. At short stand-off distances, these explosives could damage soft tissue such as lungs and eardrums and, at larger stand-off distances, these explosives could create debris that would impact the occupants. If a suspicious package is located within the building, the occupants would most likely be evacuated through exits that would lead them away from the potential threat. If, however, the occupants must be moved to a safe room, this space must be surrounded by a substantial structural wall or a reinforced masonry wall to limit the extent of debris.

Although small weights of explosives are not likely to produce significant blast loads on the roof, low-rise structures may be vulnerable to blast loadings resulting from large weights of explosives at large stand-off distances that may sweep over the top of the building. The blast pressures that may be applied to these roofs are likely to far exceed the conventional design loads and, unless the roof is a concrete deck or concrete slab structure, it may be expected to fail. There is little that can be done to increase the roof's resistance to blast loading that doesn't require extensive renovation of the building structure. Therefore, safe rooms should be located at lower floors, away from the roof debris that may rain down in response to blast loading.

The building's lateral load resisting system, the structural frame or shear walls that resist wind and seismic loads, will be required to receive the blast loads that are applied to the exterior façade and transfer them to the building's foundation. This load path is typically through the floor slabs that act as diaphragms and interconnect the different lateral resisting elements. The lateral load resisting system for a school building depends, to a great extent, on the type of construction and region. In many cases, low-rise buildings do not receive substantial wind and seismic forces and, therefore, do not require substantial lateral load resisting systems. Because blast loads diminish with distance, a package sized explosive threat is likely to locally overwhelm the façade, thereby limiting the force that may be transferred to the lateral load resisting system. However, the intensity of the blast loads that may be applied to the building could exceed the design limits for most conventional school construction. As a result, the building is likely to be subjected to large inelastic deformations that may produce severe cracks to the structural and nonstructural partitions. There is little that can be done to upgrade the existing school structure to make it more flexible in response to a blast loading that doesn't require extensive renovation of the building. Safe rooms should, therefore, be located close to the interior shear walls or reinforced masonry walls in order to provide maximum structural support in response to these uncharacteristically large lateral loads.

In addition to the hazard of impact by façade debris propelled into the building or roof damage that may rain down, the occupants may also be vulnerable to much heavier debris resulting from structural damage. Progressive collapse occurs when an initiating localized failure causes adjoining members to be overloaded and fail, resulting in an extent of damage that is disproportionate to the originating region of localized failure. The initiating localized failure may result from a sufficiently sized parcel bomb that is in contact with a critical structural element or from a vehicle sized bomb that is located at a short distance from the structure. However, a large explosive device at a large stand-off distance is not likely to selectively cause a single structural member to fail; any damage that results from this scenario is more likely to be widespread and the ensuing collapse cannot be considered progressive. Although progressive collapse is not typically an issue for buildings three stories or shorter, transfer girders or precast construction may produce structural systems that are not tolerant of localized damage conditions. The columns that support transfer girders and the transfer girders themselves may be critical to the stability of a large area of floor space. Similarly, precast construction that relies on individual structural panels may not be sufficiently tied together to resist the localized damage or large structural deformations that may result from an explosive detonation. As a result, safe rooms should not be located on a structure that is either supported by or underneath a structure that is supported by transfer girders unless the building is evaluated by a licensed professional engineer. The connection details for multi-story precast structures should also be evaluated before the building is used to house a safe room.

Nonstructural building components (e.g., piping, ducts, lighting units, and conduits) that are located within safe rooms must be sufficiently tied back to a competent structure to prevent failure of the services and the hazard of falling debris. To mitigate the effects of in-structure shock that may result from the infilling of blast pressures through damaged windows, the nonstructural systems should be located below the raised floors or tied to the ceiling slabs with seismic restraints.

Safe rooms in existing school buildings should be selected to provide the space required to accommodate the school population; should be centrally located to allow quick access from any location within the building; should be enclosed with fragment mitigating partitions or façade; and should be within robust structural systems that will resist collapse. These large spaces are best located at the lower floors, away from a lightweight roof and exterior glazing elements. If such a space does not exist within the existing school structure, the available spaces may be upgraded to achieve as many of these attributes as possible. This will involve the treatment of the exterior façade with fragment mitigating films, blast curtains, debris catch systems, spray-on applications of elasto-polymers to unreinforced masonry walls, hardening of select columns and slabs with composite fiber wraps, and steel jackets or concrete encasements. Fragment mitigating and structural upgrades and recommendations for blast protection are discussed in the following sections.

6.10 FRAGMENT MITIGATING UPGRADES

The conversion of existing construction to provide blast-resistant protection requires upgrades to the most fragile or brittle elements enclosing the safe room. Failure of the glazed portion of the façade represents the greatest hazard to the occupants. Therefore, the exterior glazed elements of the school façade and, in particular, the glazed elements of the designated safe rooms, should be protected with a FRF, also commonly known as anti-shatter film (ASF), "shatter-resistant window film" (SRWF), or "security film." These materials consist of a laminate that will improve post-damage performance of existing windows. Applied to the interior face of glass, ASF holds the fragments of broken glass together in one sheet, thus reducing the projectile hazard of flying glass fragments. See FEMA 426 *Reference Manual to Mitigate Potential Terrorist Attacks Against Buildings* for more information.

Most ASFs are made from polyester-based materials and coated with adhesives. They are available as clear, with minimal effects to the optical characteristics of the glass, and tinted, which provide a variety of aesthetic and optical enhancements and can increase the effectiveness of existing heating/cooling systems. Most films are designed with solar inhibitors to screen out ultraviolet (UV) rays and are available treated with an abrasion resistant coating that can prolong the life of tempered glass.[6] However, over time, the UV absorption damages the film and degrades its effectiveness.

According to published reports, testing has shown that a 7-mil thick film, or specially manufactured 4-mil thick film, is the minimum thickness that is required to provide hazard mitigation from blast. Therefore, a 4-mil thick ASF should be utilized only if it has demonstrated, through explosive testing, that it is capable of providing the desired hazard level response.

The application of security film must, at a minimum, cover the clear area of the window. The clear area is defined as the portion of the glass unobstructed by the frame. This minimum applica-

[6] Abrasions on the faces of tempered glass reduce the glass strength.

tion, termed daylight installation, is commonly used for retrofitting windows. By this method, the film is applied to the exposed glass without any means of attachment or capture within the frame. Application of the film to the edge of the glass panel, thereby extending the film to cover the glass within the bite, is called an edge to edge installation and is often used in dry glazing installations. Other methods of retrofit application may improve the film performance, thereby reducing the hazard; however, these are typically more expensive to install, especially in a retrofit situation.

Although a film may be effective in keeping glass fragments together, it may not be particularly effective in retaining the glass in the frame. ASF is most effective when it is used with a blast tested anchorage system. Such a system prevents the failed glass from exiting the frame.

The wet glazed installation, a system where the film is positively attached to the frame, offers more protection than the daylight installation. This system of attaching the film to the frame reduces glass fragmentation entering the building. The wet glazing system utilizes a high strength liquid sealant, such as silicone, to attach the glazing system to the frame. This method is more costly than the daylight installation.

Securing the film to the frame with a mechanically connected anchorage system further reduces the likelihood of the glazing system exiting the frame. Mechanical attachment includes anchoring methods that employ screws and/or batten strips that anchor the film to the frame along two or four sides. The mechanical attachment method can be less aesthetically pleasing when compared to wet glazing because additional framework is necessary and is more expensive than the wet glazed installation.

Window framing systems and their anchorage must be capable of transferring the blast loads to the surrounding walls. Unless the frames and anchorages are competent, the effectiveness of the attached films will be limited. Similarly, the walls must be able to withstand the blast loads that are directly applied to them and accept the blast loads that are transferred by the windows. The strength of these walls may limit the effectiveness of the glazing upgrades.

If a major rehabilitation of the façade is required to improve the mechanical characteristics of the building envelope, a laminated glazing replacement is recommended. Laminated glass consists of two or more pieces of glass permanently bonded together by a tough plastic interlayer made of polyvinyl butyral (PVB) resin. After being sealed together, the glass "sandwich" behaves as a single unit. Annealed, heat strengthened, tempered glass, or polycarbonate glazing can be mixed and matched between layers of laminated glass in order to design the most effective lite for a given application. When fractured, fragments of laminated glass tend to adhere to the PVB interlayer, rather than falling free and potentially causing injury.

Laminated glass can be expected to last as long as ordinary glass provided it is not broken or damaged in any way. It is very important that laminated glass is correctly installed in order to ensure long life. Regardless of the degree of protection required from the window, laminated glass needs to be installed with adequate sealant to prevent water from coming in contact with the edges of the glass. A structural sealant will adhere the glazing to the frame and allow the PVB interlayer to develop its full membrane capacity. Similar to attached film upgrades, the window frames and anchorages must be capable of transferring the blast loads to the surrounding walls.

Blast curtains are made from a variety of materials, including a warp knit fabric or a polyethylene fiber. The fiber can be woven into a panel as thin as 0.029 inch that weighs less than 1.5 ounces per square foot. This fact dispels the myth that blast curtains are heavy sheets of lead that completely obstruct a window opening and eliminate all natural light from the interior of a protected building. The blast curtains are affixed to the interior frame of a window opening and essentially catch the glass fragments produced by a blast wave. The debris is then deposited on the floor at the base of the window. Therefore, the use of these curtains does not eliminate the possibility of glass fragments penetrating the interior of the occupied space, but instead limits the travel distance of the airborne debris. Overall, the hazard level to occupants is significantly reduced by the implementation of the blast curtains. However, a person sitting directly adjacent to a window outfitted with a blast curtain may still be injured by shards of glass in the event of an explosion.

The main components of any blast curtain system are the curtain itself, the attachment mechanism by which the curtain is affixed to the window frame, and either a trough or other retaining mechanism at the base of the window to hold the excess curtain material. The blast curtain with curtain rod attachment and sill trough differ largely from one manufacturer to the next. The curtain fabric, material properties, method of attachment, and manner in which they operate all vary, thereby providing many options within the overall classification of blast curtains. This fact makes blast curtains applicable in many situations.

Blast curtains differ from standard curtains in that they do not open and close in the typical manner. Although blast curtains are intended to remain in a closed position at all times, they may be pulled away from the window to allow for cleaning, blind or shade operation, or occupant egress in the case of fire. However, the curtains can be rendered ineffective if installed such that easy access would provide opportunity for occupants to defeat their operation. The color and openness factor of the fabric contributes to the amount of light that is transmitted through the curtains and the see-through visibility of the curtains. Although the color and weave of these curtains may be varied to suit the aesthetics of the interior décor, the appearance of the windows is altered by the presence of the curtains.

The curtains may either be anchored at the top and bottom of the window frame or anchored at the top only and outfitted with a weighted hem. The curtain needs to be extra long with the surplus either wound around a dynamic tension retainer or stored in a reservoir housing. When an explosion occurs, the curtain feeds out of the receptacle to absorb the force of the flying glass fragments. The effectiveness of the blast curtains relies on their use and no protection is provided when these curtains are pulled away from the glazing.

Rigid catch bar systems have been designed and tested as a means of increasing the effectiveness of laminated window upgrades. Laminated glazing is designed to hold the glass shards together as the window is damaged; however, unless the window frames and attachments are upgraded as well to withstand the capacity of the glazing, this retrofit will not prevent the entire sheet from flying free of the window frames. The rigid catch bars intercept the laminated glass and disrupt their flight; however, they are limited in their effectiveness, tending to break the dislodged façade materials into smaller projectiles.

Rigid catch bar systems collect huge forces upon impact and require substantial anchorage into a very substantial structure to prevent failure. If either the attachments or the supporting structure are incapable of restraining the forces, the catch system will be dislodged and become part of the debris. Alternatively, the debris may be sliced by the rigid impact and the effectiveness of the catch bar will be severely reduced.

Flexible catch bars can be designed to absorb a significant amount of the energy upon impact, thereby keeping the debris intact and impeding their flight. These systems may be designed to effectively repel the debris and inhibit their flight into the occupied spaces. These systems may be designed to repel the debris from the failed glazing as well as the walls in which the windows are mounted. The design of the debris restraint system must be strong enough to withstand the momentum transferred upon impact and the connections must be capable of transferring the forces to the supporting slabs and spandrel beams. However, under no circumstances can the design of the restraint system add significant amounts of mass to the structure that may be dislodged and present an even greater risk to the occupants of the building.

Cables are extensively used to absorb significant amounts of energy upon impact and their flexibility makes them easily adaptable to many situations. The diameter of the cable, the spacing of the strands, and the means of attachment are all critical in designing an effective catch system. These catch cable concepts have been used by protective design window manufacturers as restraints for laminated lites. The use of cable systems has long been recognized as an effective means of stopping massive objects moving at high velocity. To confirm the adequacy of the cable catch system to restrain the debris resulting from an explosive event, an analytical simulation or a physical test is required.

High performance energy absorbing cable catcher systems retain glass and frame fragments and limit the force transmitted to the supporting structure. These commercially available retrofit products consist of a series of ¼-inch diameter stainless steel cables connected with a shock-absorbing device to an aluminum box section, which is attached to the jambs, the underside of the header, and the topside of the sill. The energy absorbing characteristics allow the catch systems to be attached to relatively weakly constructed walls without the need for additional costly structural reinforcement. To reduce the possibility of slicing the laminated glass, the cable may either be sheathed in a tube or an aluminum strip may be affixed to the glass directly behind the cable.

Unreinforced CMU walls provide limited protection against air-blast due to explosions. When subjected to overload from air-blast, brittle unreinforced CMU walls will fail and the debris will be propelled into the interior of the structure, possibly causing severe injury or death to the occupants. This wall type has been prohibited for new construction where protection against explosive threats is required. Existing unreinforced CMU walls may be retrofitted with a sprayed-on polymer coating to improve their air-blast resistance. This innovative retrofit technique takes advantage of the toughness and resiliency of modern polymer materials to effectively deform and dissipate the blast energy while containing the shattered wall fragments. Although the sprayed walls may shatter in a blast event, the elastomer material remains intact and contains the debris.

The blast mitigation retrofit for unreinforced CMU walls consists of an interior and optional exterior layer of polyurea applied to exterior walls and ceilings. The polyurea provides a ductile and resilient membrane that catches and retains secondary fragmentation from the existing concrete block as it breaks apart in response to an air-blast wave. These fragments, if allowed to enter the occupied space, are capable of producing serious injury and death to occupants of the structure.

In lieu of the elastomer, an aramid (Geotextile) debris catching system may be attached to the structure by means of plates bolted through the floor and ceiling slabs. Similar to the elastomer retrofit, the aramid layer does not strengthen the wall; instead, it restrains the debris that would otherwise be hurled into the occupied spaces.

6.11 STRUCTURAL UPGRADES

It may not be possible for existing construction to be retrofitted to limit the extent of collapse to one floor on either side of the failed column. If the members are retrofitted to develop catenary behavior, the adjoining bays must be upgraded to resist the large lateral forces associated with this mode of response. This may require more extensive retrofit than is either feasible or desirable. In such a situation, it may be desirable to isolate the collapsed region rather than risk propagating the collapse to adjoining bays. The retrofit of existing structures to protect against a potential progressive collapse resulting from the detonation of a terrorist explosive threat may, therefore, best be achieved through the localized hardening of vulnerable columns. These columns need only be upgraded to a level of resistance that balances the capacities of all adjacent structural elements. At greater blast intensities, the resulting damage would be extensive and termed global collapse rather than progressive collapse. Attempts to upgrade the structure to conform to the alternate path approach will be invasive and potentially counterproductive. Care must be taken not to weaken a structure in the attempt to make it more robust.

Conventionally designed columns may be vulnerable to the effects of explosives, particularly when placed in contact with their surface. Stand-off elements, in the form of partitions and enclosures, may be designed to guarantee a minimum stand-off distance; however, this alone may not be sufficient. Additional resistance may be provided to reinforced concrete structures by means of a steel jacket or a carbon fiber wrap that effectively confines the concrete core, thereby increasing the confined strength and shear capacity of the column, and holds the rubble together to permit it to continue carrying the axial loads. The capacity of steel flanged columns may be increased with a reinforced concrete encasement that adds mass to the steel section and protects the relatively thin flange sections. The details for these retrofits must be designed to resist the specific weight of explosives and stand-off distance.

The floor slabs are typically designed to resist downward gravity loading and have limited capacity to resist uplift pressures or the upward deformations experienced during a load reversal. Therefore, floor slabs that may be subjected to significant uplift pressures, such that they overcome the gravity loads and subject the slabs to reversals in curvature, require additional reinforcement. If the slab does not contain this tension reinforcement, it must be supplemented with a lightweight carbon fiber application that may be bonded to the surface at the critical locations. Carbon fiber reinforcing mats bonded to the top surface of slabs would strengthen the floors for upward loading and reduce the likelihood of slab collapse from blast infill uplift pressures as well as internal explosions in mailrooms or other susceptible regions. This lightweight high tensile strength material will supplement the limited capacity of the concrete to resist these unnatural loading conditions. An alternative approach may be to notch grooves in the top of concrete slabs and epoxy carbon fiber rods into grooves; although this approach may offer a greater capacity, it is much more invasive and has not been evaluated with explosive testing.

RECOMMENDATIONS FOR BLAST PROTECTION

The following actions are recommended for blast protection:

- Increase the level of protection against an external detonation by applying any one of the fragment mitigating options summarized above to a renovated school gymnasium or auditorium safe room. The effectiveness of these measures will depend on advanced notification of a suspicious device and the distance from the explosive source.
- Develop plans, procedures, and training for sheltering in place as a protective action against a remote explosive threat. To support this protective measure, define a rapid notification system (public address system) and safe evacuation routes.
- Develop security procedures specific to entry screening for suspicious objects to reduce vulnerability to internal detonation. However, the decision to implement these procedures should be made on a case by case basis following a thorough risk analysis for the facility.