THE EFFECTIVE USE OF NEW MATERIALS AND METHODOLOGIES FOR BLAST MITIGATION IN NEW AND RENOVATED FACILITIES BY THE ARMED SERVICES

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The opinions and conclusions expressed herein are those of the student author and do not necessarily represent the views of the U.S. Army Command and General Staff College or any other governmental agency. (References to this study should include the foregoing statement.)

ABSTRACT

THE EFFECTIVE USE OF NEW MATERIALS AND METHODOLOGIES FOR BLAST MITIGATION IN NEW AND RENOVATED FACILITIES BY THE ARMED SERVICES, by MAJ Scott A. Warner, 112 pages.

Since 1993, there have been numerous terrorist bombing attacks toward US facilities located on US or US controlled soil. This fact has motivated government organizations to take a hard look at how their facilities are constructed and what would be the consequences if a device were detonated in the vicinity to damage the facilities and injure or kill the occupants. The armed services have a large role to play in this effort, based on the number and location of installations they own or operate and the threat probability of a future attack. In response, private industry and government research facilities have developed a significant number of innovations in materials and methodologies for building construction and renovation that are now available in order to help mitigate the damage to facilities and occupants as a result of explosive blast. These innovations have been directly and indirectly prompted by the fear of other attacks on US soil, plus the recognition by private industry of the potential lucrative market. The armed services have made efforts to test and incorporate these materials and methodologies into their building codes and standards; the extent of these incorporations is the focus of this research.

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ACRONYMS

AB	Air Base (located outside US states or territories)
AFB	Air Force Base (located in US states or territories)
AFRL	Air Force Research Laboratory
AMPTIAC	Advanced Materials and Processes Technology Information Analysis Center
ANFO	Ammonium nitrate and fuel oil (explosive)
ARMCO	American Rolling Mill Company, maker of specialty steel products (including revetment materials)
ASF	Antishatter film
AT	Antiterrorism
ATF	Bureau of Alcohol, Tobacco, and Firearms
BBN	Bomb blast net (installed inside windows to catch flying glass)
BEEM	Blast Effects Estimation Model (software published by USACE PDC)
CIA	Central Intelligence Agency
CMU	Concrete masonry unit
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
DOJ	Department of Justice
DOS	Department of State
DTIC	Defense Technical Information Center
DTRA	Defense Threat Reduction Agency
ERDC	US Army Engineer Research and Development Center

FAA	Federal Aviation Administration
FBI	Federal Bureau of Investigation
FEMA	Federal Emergency Management Agency
FP	Force Protection
GSA	General Services Administration
HHE	High hazard environment
HQ	Headquarters
IED	Improvised Explosive Device
ISC	Interagency Security Committee
JWAC	Joint Warfare Analysis Center
MILCON	Military Construction Program
NSA	National Security Agency
OST	Office of Special Technology
PDC	US Army Corps of Engineers Protective Design Center
RPG	Rocket Propelled Grenade
TNT	Trinitrotoluene (explosive agent)
TSWG	Technical Support Working Group
UFC	Unified Facilities Criteria
US	United States (of America)
USACE	US Army Corps of Engineers
USIS	United States Information Service
USO	United Service Organizations
WTC	World Trade Center, New York City, NY

ILLUSTRATIONS

CHAPTER 1

INTRODUCTION

> The issue of ensuring structural integrity from explosive blasts has been an active topic with the military and national security communities for years. Such concerns arose initially in response to bombing threats during World War II; however, they continued through the Cold War, and more recently these concerns have grown with the increase in terrorism worldwide. A large body of theoretical and empirical knowledge regarding explosions and their effects has been developed as a result of research and tests sponsored by US government agencies, including the Defense Nuclear Agency and the uniformed services. (1995, 1)
>
> Commission on Engineering and Technical Services,
> *Protecting Buildings from Bomb Damage*

Since 1993, there have been numerous bomb related attacks on United States (US) facilities located on US controlled soil. Consequently, organizations have taken a hard look at how their facilities are constructed and what would occur if an explosive device were detonated in close proximity to damage the facilities and injure or kill the occupants. The armed services have a large role to play in this effort, due the number and location of installations they own or operate. During the same period, directly prompted by the fear of other attacks on US soil, there have been numerous innovations in materials and methodologies for building construction and renovation that are now available in order to help mitigate the destruction of facilities due directly and indirectly to explosive blast. The armed services have made efforts to test and incorporate these materials and methodologies into their building codes and standards; the extent of these incorporations is the focus of this thesis.

Accordingly, an examination of the innovations in materials and methodologies since the World Trade Center (WTC) bombing in 1993 is important. What begs to be determined is whether or not the armed services are making effective use of these innovations, by incorporating the ideas within building standards and the planning process for permanent building construction and renovation projects. The formal final thesis topic is: The effective use of new materials and methodologies for blast mitigation in new and renovated facilities by the armed services.

Background

Although the bombing of buildings has been a common tactic exercised by terrorists, it has not been until the last decade or so that the US government has taken a hard look at how permanent, main base facilities could be affected directly and indirectly by localized explosions. Up until 1993 the US had limited nonmilitary, terrorist attacks involving explosive devices on its facilities, either within its borders or overseas. There were a few exceptions, primarily overseas. A literary search yielded only two meeting the criteria of explosive attacks on facilities in the US: a Wall Street bar and a bathroom at the Department of State (DOS) in January 1975, both of which were limited in scope and executed by individuals rather than an organized opposing force. Some of the others outside the US include: VII Corps Headquarters (HQ) in Germany in 1972, Ramstein Air Base (AB) Germany in 1981 (see Figure 1), the US Embassy in Beirut in 1983, the Marine Barracks in Beirut in 1983, Rhein-Main AB Germany in 1985, the Naples United Service Organizations (USO) Club in 1988, the US Embassy in Peru in 1990 and an attempted attack at the Ambassador's House in Indonesia and United States Information Service (USIS) Library in Manila in 1991 (US Department of State 2004). These incidences, while not trivialized by the American public, were still viewed with some level of detachment. The public was concerned from a third-person point of view; the general public viewed the incidents with interest but with emotional detachment. However, that changed on 26 February 1993 when Tower 1 of the WTC was the target of a vehicle borne improvised explosive device (IED), complete with cyanide gas that was to be released in the area as a result of the explosion. Although the bomb was not large enough to topple the building and the cyanide was consumed in the initial explosion, it was perceived as a successful terrorist bombing on US soil by an organized enemy force specifically targeting Americans and the American way of life (symbolized by the WTC). The year 1993 marks the beginning of a new era in America; an age where Americans no longer feel safe on their own home ground, within the confines of their own borders.

Figure 1. HQ US Air Forces in Europe, Ramstein AB Germany, August 1981
Source: Captain Elizabeth A. Ortiz, "20 years later, people still recall Ramstein bombing," *US Air Forces in Europe News Service;* available from http//www.usafe.af.mil/news/nes01/uns01289.htm; Internet; accessed 8 March 2005.

Unfortunately, the trend that followed further reinforced the fear that Americans were no longer safe on US or US controlled soil. Further incidents included the 1995 Alfred P. Murrah Federal Building bombing (which also introduced the horrifying prospect that the enemy may be an American citizen instead of a foreign terrorist); the 1995 bombing of a military compound in Riyadh, Saudi Arabia; the 1996 Centennial Olympic Park bombing (see Figure 2); the 1996 Khobar Towers bombing; the 1998 US embassy bombings; the 11 September 2001 attacks on the WTC and the Pentagon; and the Riyadh, Saudi Arabia, bombings in 2003 and 2004 (see Figure 3). As one part of a concentrated effort on protecting personnel working in federal buildings and military installations, the armed services began to look at the most vulnerable facilities to determine if the structures could be improved to increase their resistance to explosive devices. They also examined what measures could be taken to minimize the potential harm to occupants from the building materials themselves, turned into deadly projectiles by the force of the explosion.

Figure 2. Centennial Olympic Park Explosion, 12 May 1996
Source: Robert Gee, "The Hunt for Eric Rudolph," *CNN Presents;* available from http://edition.cnn.com/CNN/Programs/presents/shows/rudolph/interactive/photo.gallery/content5.html; Internet; accessed 8 March 2005.

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Figure 3. Riyadh Security Building Bombing, 21 April 2004
Source: Brian Braiker, "Terror in the house of Saud," *Newsweek National News;* available from http://msnbc.msn.com/id/5241654/site/newsweek; Internet; accessed 8 March 2005.

How the Problem Looks Today

Over ten years have passed since the initial WTC bombing; it is reasonable to assume that the armed services have had ample time to discover, investigate, and incorporate the new materials and methodologies into the building standards. All the armed services have established testing and program offices to survey and test the different types of materials and methodologies available to increase facility resistance to blast damage, second-level, and third-level effects of different explosive profiles. All the armed services have also incorporated some level of increased force protection (FP) requirements in its construction and renovation standards, as well as procedural changes meant to decrease the risk to individual facilities. To what degree all these efforts have been accomplished is a good question and, subsequently, the subject of this thesis.

The primary question is basically the thesis topic, which is: Have the armed services made effective use of innovations in materials and methodologies for blast mitigation in new and renovated facilities? In order to better answer this question, the secondary questions will help to explore this topic, namely discussing: How are the terms defined in the thesis question (innovations, new, and renovated for example)? What innovations in materials and methodologies for blast mitigation have come about? What testing has been done on new blast resistant materials in the armed services or other government agencies? What changes have the armed services made in their construction and renovation standards pertaining to blast mitigation? What additional materials and methodologies in blast mitigation do the armed services see incorporating in the future? Has there been a quantifiable improvement noticed or observed since implementing any new materials and methodologies? Each one of these questions will help to spread light across the relevant focus area, by looking at what technologies are available off the shelf, what technologies the armed services are testing within their own resource limitations, what methodologies and materials have been deemed appropriately effective and added to the facility standards, and what trends are being explored for future incorporation. In addition, some discussion time will be spent looking at any situations where incorporation of improved methodologies and materials made a significant real-world contribution.

Limiting the Broad Scope of "Blast Mitigation"

In order to better delimit the information present within the thesis, the focus is on only building construction and renovation materials and methodologies. The discussion does not include any procedural mitigation tactics, such as standoff distances, vehicle inspections, or bomb detection devices, other than to perhaps identify them and mention them in passing. Therefore, the scope is limited to issues related to facility siting, building materials, construction techniques, and other facility strengthening methods. Additionally, the scope is further focused to permanent facilities, built at main bases through the military construction program (MILCON) or an equivalent program. The analysis neither addresses temporary or semi permanent facilities built for expedient reasons, nor does it incorporate methodology and materials used for wartime hardening of facilities (sandbag emplacements, temporary earth berms, American Rolling Mill Company (ARMCO) revetment, and other contingency type solutions). Finally, the scope is limited to vehicle bombs, IEDs, and other traditionally nonmilitary applications with the exception of rocket propelled grenades (RPGs). This is a significant limitation, because it drives the assumption that the threat is posed by delivered devices, either by hand or by vehicle, rather than military munitions (heavy artillery, tank rounds, air-delivered munitions, guided missiles, and other munitions). The distinction here is penetrability and portability; the assumption is that the threat is from nonstate actors, acting in small groups with minimal technologies, who in all probability neither have access to nor the ability to covertly deliver threats, such as missiles, penetrating weapons, or antiarmor type military munitions. A probable scenario would be an IED, delivered by hand and detonated by a suicide switch. Another would be an improvised vehicle bomb, driven and detonated in close proximity to a target facility.

Possible Problems and Potential Solutions

One anticipated problem was the lack of available information on obtaining verifiable, quantifiable improvement observed as a result of implementing new materials and methodologies for blast mitigation. Test data on these improvements is plentiful, which is revealing in its own right, but unless there is an actual incident which occurs on an application utilizing improved materials and methodologies, it is impossible to get actual quantifiable information. At the time the thesis was conceived, the only discovered case was that of the Pentagon aircraft strike on 11 September 2001. In this case, the 757 airliner that was purposely crashed into the Pentagon hit a wedge of the facility that had just undergone renovations, which included certain upgraded force protection measures. It remains to be seen whether or not this can be considered equitable to a vehicle bomb, primarily due to additional kinetic energy provided by the sheer mass of the aircraft and the velocity introduced into the equation. While this case will provide some good information, it unfortunately is a singular case and cannot be contrasted and compared significantly with any other known cases. To overcome this shortfall, additional sources were used to make a comparison, including test data, case studies and other writings as determined to be applicable to the topic. Simulation software was also considered as an aid in testing materials and methodologies, specifically as an alternative to real-world testing and forensic analysis of actual events.

CHAPTER 2

LITERATURE REVIEW

Force protection is a common topic in the printed media these days, in terms of finding research material. However, the general subject of force protection is a very wide topic, encompassing an entire realm of potential threats, potential targets, appropriate preparations, technological innovations, environmental considerations, and operational procedures that interlock to provide a comprehensive, complete response to potential threats. The field of material is reduced dramatically when delimited to the scope of this thesis, which focuses the potential threat to explosive devices deployed against a particular subset of military installations. In addition, the topic further delimits the field of material by eliminating operational procedures from the analysis (which includes such topics as security checkpoints, vehicle control points, stand-off distances, increased physical security, and other procedural security measures) and focusing strictly on the engineering aspects of blast mitigation (which includes such items as facility hardening, blast absorption, blast channeling, and other engineering solutions). There was no problem finding the information needed to complete the analysis; in actuality there was an abundance of material that needed to be sifted through to find what was truly applicable to the subject matter.

Innovations in Materials

Innovations in materials and methodologies have been numerous and plentiful in the last decade due to the increased fear of terrorist attack on US soil, as well as the healthy entrepreneurial spirit of the American people. A simple search on the Internet uncovers hundreds of materials designed to mitigate blast effect, such as coated windows, interlocking construction panels, elastic polymer coatings, and others. Most have been tested in some capacity by creditable organizations and therefore were valid for inclusion in this thesis. The materials are categorized into general categories and different details were examined and acknowledged within each general category. The following general categories were used: doors, windows, curtains, wall material, applied coatings, and exterior structures (to include walls, berms, and other features). Each general category was examined from two different aspects: applicability to new construction and to renovation. As part of the continuing research procedure, various Internet locations were explored to determine material identified as applicable to blast mitigation. Primarily, these were found to be private sector websites advertising their products, although some did lead to individual test results displayed by the manufacturer. In addition, recent test results from US government sponsored testing were examined to get a clear picture of materials available and identified as promising, to include: *The Divine Buffalo 9 Test Event: Results of Structural Response and Windows Experiments* (1999), *Retrofitting Existing Buildings to Resist Explosive Threats* (2003), *Lightweight Blast-Resistant Doors for Retrofit Protection Against the Terrorist Threat* (2003), and *Sealed Blast-Resistant Windows for Retrofit Protection Against the Terrorist Threat* (2003).

Innovations in Methodologies

Similar to materials, construction methodologies were examined to determine if they had been implemented or were being developed as part of the effort to mitigate the effects of explosive blasts on facilities. Methodologies are even more polarized than materials when it comes to determining what pertains to new construction and to renovation, so that was the first discriminator considered when analyzing methodologies.

The methodologies were divided into general categories and analyzed within each category. Categories identified included design considerations (siting issues, facility layouts, landscaping, and other features), blast redirection, and energy absorption. A few of the primary sources utilized to address categories of methodologies included: *Primer for Design of Commercial Buildings to Mitigate Terrorist Attacks* (2003); *Protection Against Blast Effects from Terrorist Vehicle Bombs* (1997); and *Retrofitting Existing Buildings to Resist Explosive Threats* (2003).

Testing of Materials and Methodologies

Testing results and procedures for evaluating these materials by the armed services were equally plentiful, since the test results in most cases of these materials are unclassified material and therefore freely available from the various federal government organizations. In addition, there were tests that were commissioned in the private sector by the armed services, or that were completed independently and later incorporated by the armed services. Information on the test results and the perceived usefulness of the material by the armed services were included in the report to some extent. For all intents and purposes, delving deeply into the details of the testing, particularly the approach and procedure, was avoided unless for some reason those aspects were relevant to the use and incorporation of the material or methodology in an actual situation. The focus of the thesis drove interest in testing primarily from an empirical point of view: what has been tested, who did the testing, how were the results interpreted, and how (and when) were the results incorporated into real-world design characteristics and material standards. In addition to the testing documents listed in the two previous subheadings, other testing material sources such as *Polymer Materials for Structural Refit* (2001) were included.

Incorporating Innovation into Design Guides and Standards

Identifying and validating changes made to the armed services' design guides and standards were a bit more challenging, but not overly problematic. The information was readily available through the Internet or from various armed services' libraries. The first step was to try and identify the base document, some sort of guidance that would provide a common foundation for blast mitigation and force protection across all the services, and possibly across all the federal organizations as well. One document was discovered that does provide a common reference point for all the military services, published by the Department of Defense (DOD): the *Unified Facilities Criteria: Department of Defense Minimum Antiterrorism Standards for Buildings* (2002).

Taking it to the next level down, the analysis attempted to discover some of the documents that further delineate blast mitigation, documents that may be service specific. Some representative samples of these sources include the *User's Guide on Protection Against Terrorist Vehicle Bombs* (1998) from the Naval Facilities Engineering Service Center and the *Vehicle Bomb Mitigation Guide* (2002) from the Air Force Force Protection Battlelab. By surveying these documents, a determination was made on the extent of force protection, specifically blast mitigation, which has been incorporated into the service specific program.

During the research process, a special effort was made to discover information of a chronological nature that would help to delineate what changes were made, when the changes were incorporated, and why. However, the lack of information found should not be considered to be a detriment to the analysis based on the difficulty of ascertaining the information. Rather, the focus should be on the entire document and when it became effective, not so much the individual aspects (i.e., which details were incorporated in 1994, which in 1995, and so on). A possible recommendation for further study would be to continue the research process to discover a document or group of documents that may help to construct a timeline laying out what aspects were adopted in what order and as a result of what (stimulus, test results, or innovation). What information could be found was found in the February 2003 Advanced Materials and Processes Technology Information Analysis Center (AMPTIAC) journal, *AMPTIAC Quarterly*, which was a special issue focusing on protecting people at risk. Two articles were particularly noteworthy: "DOD Protective Design Manuals Have Wide Application" and "Protecting Personnel at Risk: DOD Writes Anti-Terrorism Standards to Protect People in Buildings."

Future Trends for Blast Mitigation Materials and Methodologies

In order to provide a future aspect of the analysis, an attempt was made to identify and predict (based on available solid data) what would be the future trends for blast mitigation materials and methodologies. To do this, emerging technologies in the construction industry, crossover studies in nontraditional construction materials that could have applicability for blast mitigation, and white papers or other type documents from creditable sources in this subject matter area were examined.

The Air Force, Army, and Navy all have testing centers that routinely conduct testing on materials and construction methodologies to find more innovative, effective, and efficient ways of providing facilities that are structurally sound and to provide at least a minimum of protection to the members inside the facility from blast effects (among other things). Based on their experiences, they can provide an indication of things to come, specifically possible future trends in blast mitigation materials and construction methodologies in the military and commercial marketplace.

Quantifiable Improvement from Incorporation

An important angle to this analysis was determining if "lessons were learned" as applied toward the incorporation of blast mitigation materials and methodologies. Specifically, the thesis attempts to conclude whether or not implementation of identified improvements in materials and methodologies have made a quantifiable difference in improvement of resistance to blast effects. Blast mitigation is one of those phenomena where it is hard to quantify improvement; it is much easier to see what does not work than what does work. To further compound the problem, to really see if a facility has an improved resistance against blast effects, it must be submitted to the actual effects, which is not realistic. Therefore, the thesis attacks this problem from three fronts: the results of testing run on materials and building methodologies by the armed forces and other organizations; simulations conducted on software designed to measure blast effects of materials in certain configurations; and actual cases where improved construction materials and methodologies were involved in a real-world blast event.

An example of test results incorporated was a series of tests run by Advanced Technology and Research Corporation under contract by the Office of Naval Research on sandwich panels for building construction, which incorporate a high strength face material coupled with high energy absorbing core material (Goeller and Ruben 2003, 5). Representative of most test results, these results outline the objective of the testing, the testing approach, the details of the testing itself, and the preliminary results. There are other test results that were examined as well, to include the tests specified in the materials and methodologies sections above.

Through the initial research material identification process, mention was made of several software programs either developed by the US government or purchased from government contractors that allow researchers to test possible blast mitigation improvements in a virtual environment. This ability has an extremely high potential, because it allows researchers to screen potential improvements at a relatively low cost prior to spending the high costs associated with a series of field tests. Therefore, materials and methodologies can be initially screened on the software, and then prioritized for field testing based on the results of that virtual testing. Two examples of this software include: the US Army Corps of Engineers (USACE) Blast Effects Estimation Model (BEEM) and Northup Grumman’s Blast/FX. Both BEEM and Blast/FX were examined, and their perceived effectiveness was incorporated into the analysis.

Finally, case studies of various actual events were analyzed in order to determine if improvements pertaining to blast mitigation were incorporated into the design, construction, and renovation prior to the incident. The analysis attempts to answer various important questions, such as: How did the improvements affect the severity of the damage to the structure? Other case study information on several recent blast incidents that present analysis of the event and offer some insights on points of failure and performance of key construction materials and building construction details was incorporated as well. Two of these case studies are: “Blast Loading and Response of Murrah Building,” (1997) which examines the forensics of the Alfred P. Murrah Federal

Building bombing in 1995, and *The Pentagon Building Performance Report*, concerning the damage after the Pentagon aircraft strike on 11 September 2001.

Key Sources of Information

Based on initial research, a couple of sources of information proved valuable for the thesis, and are considered key sources. The first, by far, was the February 2003 issue of the *AMPTIAC Quarterly* journal, a special issue which addressed protecting people at risk and focused on how DOD research is reducing the impact of terrorism. Every article in this journal was relevant in some manner or another to the theme of the thesis, and quite a few of the articles were used as sources of information. Another valuable source was the *Unified Facilities Criteria: DOD Minimum Antiterrorism Standards*, which is really the keystone document for the DOD and all the services when it comes to incorporating blast mitigation innovations in materials and methodologies into new construction and renovation projects.

Envisioned Contribution to the Field

The purpose for researching and writing this thesis was to provide a clear view of what steps the armed services have taken post the 1993 WTC bombing to protect people and facilities from the very real threat of improvised munitions deployed against military and civilian targets. In addition, it was intended to highlight the steps the armed services have not taken, and possibly point out some upcoming steps that could be taken based on technology that is available or soon to be available in the near future. Finally, the results and recommendations may be useful as a means to better prepare facilities for possible future attacks and reduce the terrorist threat to American citizens and servicemen home and abroad.

CHAPTER 3

RESEARCH METHODOLOGY

Laying the Groundwork

After examination of the thesis topic for applicable research methodology, it appeared that the most appropriate path of approach would be determined by an examination of each secondary question. In addition, a determination of philosophy on what direction to approach the answer of the primary question would also be required. While this appears to be overly introspective, the subject of blast mitigation is a wide open environment, one that must be delimited not only in scope but in approach in order to reduce the necessary analysis to a digestible size. In order to define the approach, the analysis focuses on the incorporation of innovations by the armed services.

It is important to understand what is intended by the term “innovation.” Innovation is a common word, one that gets overused by the private sector to describe anything that portends to be new, creative, better than the old. Unfortunately, it has been overused both appropriately and inappropriately to the point of being rendered meaningless. However, this interpretation is solidly based on the commercial definition of the word rather than the commercialized meaning (a difficult distinction to make). From a commercial standpoint, an innovation is an idea, process, or device that has been developed, tested, marketed, and validated as an improvement over the current or previous method or material. This is distinctly different from an invention, which is an idea, process, or device that portends to be an improvement, but has not been tested, fielded, or is available commercially. Coming full circle, the intent of focusing on innovations rather than inventions is to examine those methods and methodologies that have already been proven to be effective when used as intended as part of blast mitigation system. Consequently, while test results may be referenced in order to quantify effectiveness, the analysis does not elaborate on testing, testing methodology, or any other parts of the process that transforms an invention into an innovation. The methods and materials surveyed are the commercial, off-the-shelf type, readily available in the marketplace for immediate implementation. For the intent of this thesis, an innovation is defined as: “the result of turning an invention into commercial success or widespread use, including all the steps from the inventor's idea to bringing the new item to market.”

This distinction helps to define the research methodology, by orienting more or less in the qualitative versus quantitative method. In general, the analysis utilizes a mixed methodology for research, from the group of qualitative methods. Primarily, it utilizes the case study method. Most of the information about available materials and methodologies comes from the results of published studies and from commercial vendors of off-the-shelf materials and methodologies. In addition, it utilizes the historic method. This is primarily for documenting materials and methodologies that were incorporated into policy and guidance by introducing that very guidance as a source.

The research for the thesis came from a group of different media sources, although primarily from written documents. Several identified different published works document changes in blast mitigation policy, as well as test results on numerous materials being tested for possible use in blast mitigation.

Logical Progression from Secondary Questions to Primary Question

In order to reach a logical, structured conclusion to the primary question, the analysis was fragmented into elements that, when combined, provide a supported conclusion to the analytical information provided. The primary question the thesis attempts to answer is: Have the Armed Services made effective use of innovations in materials and methodologies for blast mitigation in new and renovated facilities? This was broken down into six secondary questions, with sixteen subsidiary questions. Each secondary question was analyzed separately, bounded by the subsidiary questions to lay the framework for final conclusions and recommendations for further study.

Definition of Terms

One of the most basic secondary questions was: How are the terms defined in the thesis question? This question had multiple subsidiary questions, concentrating on defining the terms used in the thesis question, to include: What constitutes a new or renovated facility (in the context of the thesis)? What kinds of facilities are focused upon in this analysis? What is considered effective use? What constitutes innovations in materials and methodologies?

While some of these questions seem on the surface to be inanely simple, the terms used in the thesis question tend to beg more questions than provide answers. For example, consider the effective use question; just what is meant by “effective” in this sentence? Does this mean that the armed services have fully embraced the innovation? Does it mean that the armed services did not embrace the innovation, but had good reason not to? Or does it mean that the innovation has proven to be cost beneficial when considering cost and return on investment? Accurately defining the yardstick represented by the word “effective” provides significant insight to the level of innovation incorporation (or lack of incorporation). Another example is defining the subset of facilities that were examined during the analysis. What may be judged effectively used when considering HQ facilities may not be considered effective when considering aircraft hangars. The analysis provides a framework to work within in order to delimit the scope, and allows the remaining questions to render the conclusions relevant and consistent.

Innovations in Blast Mitigation Materials and Methodologies

The next secondary question was: What innovations in materials and methodologies for blast mitigations have come about? The analysis focuses on what blast mitigation innovations have become available in the public or private market that could potentially be utilized by the armed services. Within this secondary question the research was channeled into three different subsidiary questions. The first attempted to classify the innovations into distinct classes in order to better examine their effectiveness and gain some synergy in the analysis. Most of this information was derived from a market survey; the commercial sector already tends to subdivide their products into general classes. By capitalizing on this previously surveyed data, the thesis incorporates completed work to advantage during the analysis. The analysis examined each range of innovations to make a cursory judgment on whether they are feasible or not. This step helped to delimit the number of innovations available into a manageable group. As a part of this step, the analysis attempts to make a determination on what constitutes feasibility; considering such factors as cost, availability, and ease of installation. Finally, the focus is turned outside of the armed services to other government agencies, private agencies, commercial ventures, and other countries to see who else is using these innovations and gauging how much of their experience be used to benefit the analysis and the blast mitigation program for the armed services. Other organizations considered include the DOS, nongovernmental entities, engineering and security firms, and countries such as Israel and Ireland. This information was consolidated in an effort to obtain a range of innovations that are feasible for use by the armed services and are available in the marketplace.

Testing in Armed Services and Other Agencies

In order to provide full and complete coverage, one of the secondary questions is: What testing has been done on new blast resistant materials in the armed services or other government agencies? This secondary question attempts to determine who in the government (armed services and others) does blast mitigation testing, and how compatible are the test results with what the armed services deems feasible (as determined in a previous question). The analysis also looks at how this information is distributed among the different federal organizations. Finally, a case study is examined of an example test, outlining procedures, results distribution, and basic test parameters. This information came primarily from public published information available online that helped identify what past and current projects the test centers are working on.

Changes in Construction and Renovation Standards

The next area of focus was what changes have been made since approximately 1993 to the armed services' construction and renovation specification and design guides, specifically to implement and include the innovations in blast mitigation materials and methodologies that were identified in one of the previous secondary questions. The analysis attempts to answer the secondary question of: What changes have the armed services made in their construction and renovation standards pertaining to blast mitigation? As part of the analysis, some subsidiary questions were considered, including identification of the date of incorporation (if available) and whether or not the innovation has been utilized in actual projects (design or construction). Cost was also considered as a factor in implementation decisions, primarily because cost appears to be the driving factor on whether or not an innovation will be implemented. Representative samples of the armed services construction standards (including DOD and Uniform Building Code) and design guides were examined. In addition, the analysis considered the history of changes in blast mitigation construction and renovation documentation from other federal organizations as well, to examine any parallelisms or similarities that might enhance either (or both) programs.

Future Trends in Blast Mitigation

To complete the chronological circle after looking at what has been incorporated and what is currently being incorporated, the analysis makes a determination (or prediction) of what may be future innovations for the armed services to incorporate in their blast mitigation plans. This exercise will try to answer the secondary question: What additional materials and methodologies in blast mitigation do the armed services see incorporating in the future? When examined in the light of other research, these innovations are represented by current inventions that show potential, but have not reached the innovation state (i.e. are not available commercially as an off-the-shelf type product). Research within current engineering journals and other technical journals turned up a few examples of promising technology that could be incorporated as an innovation in blast mitigation.

Observations after Incorporation

The armed services, other federal organizations, and the private sector test blast mitigation materials and methodologies to determine their response to blast effects, and to project how that response will be incorporated into a facility as a whole. No matter how much individual testing is done, it is difficult to project exactly how the facility as a system will respond to a potential blast event. In that respect, the analysis looks at (the last secondary question): Has there been a quantifiable improvement noticed or observed since implementing any new materials or methodologies? Within this question, some subsidiary questions explore how to quantify an improvement in blast mitigation, in essence what criteria could be used to determine an improvement in blast effect mitigation. Only by understanding what constitutes improvement can innovations be accurately judged whether or not they met the expectations of the implementers. By conducting both a structural analysis of the facility as a whole and combining that with the individual material and methodology test results, designers can get a pretty clear view of how strong the facility is and the structural loads it will endure. This does not provide results per a specialized blast event; each blast event to be modeled would require a full and complete rework of the facility analysis. In the absence of similar real-world blast events, the analysis examined the usefulness and accuracy of blast simulation software as a means to validate the effects of implementing new materials and methodologies in full facility blast mitigation systems. Two programs were obtained and used for testing: BEEM from USACE and Blast/FX from Northrop-Grumman. Finally, the thesis analyzed a couple of case studies to determine if improvement was noted in real-life situations, where innovations were incorporated prior to a real-life blast event, or as a result of a blast event.. The two case studies examined were the Alfred P. Murrah Federal Building bombing in Oklahoma City in 1995 and the Pentagon aircraft strike on 11 September 2001.

CHAPTER 4

ANALYSIS

Building the Framework: How Should the Terms be Defined?

Force protection, while not a new idea, has experienced increased attention since the 1993 WTC bombing, especially on the military side of the house. This additional attention has expanded the field of view, requiring common terms and concepts in order to effectively communicate meaning and definition within the realm of force protection. When contemplating the topic, the boundaries may be self-evident to some, but others may view it in a different light, demonstrating a need for common meanings and definitions. Accordingly, it is important to dissect the thesis statement and question for meaning, defining each term individually and forming a common operating picture as a foundation for understanding.

Blast Mitigation

Starting at the most basic level, blast mitigation itself needs to be adequately examined. A good place to start is with an industry definition: blast mitigation can be defined as: "action that reduces or eliminates long term risk to people and property from explosive devices and their effects" (Threat Resolution Limited, 2004). While this is a good start, it needs some further refinement to meet our needs. Eliminating the "long term" descriptor is a logical first step; the thesis includes the short term, mid-level term and long term risks to personnel and property. Also, "effects" is a nebulous term that may or may not incorporate both the primary and secondary aspects of explosive damage. In the analysis section, the thesis is examining both aspects of explosive damage; for example, personnel can be injured from explosive devices through primary effects, such as the overpressure wave, or from secondary effects, such as flying glass. The goal is to protect personnel and property, regardless of the source. Therefore, rather than being redundant, adding in the terms primary and secondary will ensure clear understanding by the reader. Incorporation of these refinements yields a final definition of blast mitigation: "action that reduces or eliminates risk to people and property from explosive devices and their primary and secondary effects."

Innovations in Materials and Methodologies

The plan is to examine innovations in materials and methodologies in blast mitigation; this needs to be bound not only to ensure understanding of what was included, but just as importantly to identify what was not included in the analysis. An innovation was previously identified in chapter 3 as "the result of turning an invention into commercial success or widespread use, including all the steps from the inventor's idea to bringing the new item to market." It is important to note that this analysis is looking at aspects that have already been deemed economically and technically feasible. In other words, this thesis will examine products and procedures that are technically feasible in the commercial or government sector to validate if they are technically and economically effective for incorporation into the armed services' program. The term "materials" represents the physical products that are used for blast mitigation, while the term "methodologies" represents the actions, procedures, and techniques used to incorporate the materials. An example of materials would be reinforced concrete bricks. The bricks themselves may represent an improvement in blast mitigation properties due to their improved physical aspects. Materials, for use in this thesis, are defined as "physical products used for blast mitigation." The procedures used to build a wall of these bricks incorporating interlaced ¼ inch steel cable would be an example of a methodology. The bricks improved blast mitigation properties were further improved by how the wall was assembled; i.e. incorporating ¼ inch steel cable in the installation. Therefore, methodologies are defined as “the actions, procedures, and techniques used to incorporate materials in a blast mitigation program.”

New and Renovated Facilities

As discussed in chapter 1, the scope of the thesis was delimited to a smaller subset in order to better focus the analysis. Only permanent facilities have been included as part of the analysis, which includes those facilities built at main bases and posts through MILCON or other equivalent program. What are not included are facilities that are temporary or semi permanent, built for expedient measures or as temporary facilities awaiting future construction of permanent facilities. Therefore, tent cities, temporary housing facilities, and other similar facilities are not considered as part of this analysis. Blast mitigation and personnel protection in these facilities is not inconsequential, but blast mitigation in these types of facilities can be better accomplished through the use of contingency materials and methodologies, such as sandbag emplacements, temporary earth berms, revetments, and procedural solutions, such as stand-off distances, detection devices, increased security patrols, and other processes.

The next consideration is the definition of a new facility. From a construction point of view, a new facility is a facility that is built from the ground up and that entails additional work and design beyond that required for a renovated facility. For a new facility, a comprehensive design is required that incorporates all the work to start with an existing site and finish with a complete and usable facility. The plan must include provisions to demolish any existing structures on the proposed site, prepare the existing site for construction, build the facility, connect the facility to exterior utilities, landscape the surrounding area, and provide vehicle and pedestrian access to the facility. Therefore, blast mitigation considerations for new construction facilities include materials and methodologies pertaining to facility siting, construction materials, landscaping, utility connections, and facility access. Consequently, the final definition of a "new facility" would be "a facility constructed from the ground up, culminating with a complete and usable building and associated grounds; includes all work and materials necessary to demolish existing structures, prepare the site, construct the facility, and provide landscaping, utilities, and access." The very nature of new construction allows more flexibility in blast mitigation improvement than renovation work.

Blast mitigation in renovated facilities is more restrictive than in newly constructed facilities. Work in renovated facilities is limited in most cases to work on and in an existing structure. Renovation work can include minor work or a complete gutting of a facility, but does not include increasing the total amount of usable space. Materials and methodologies are limited to those that can be incorporated within the existing facilities, which eliminates some of the considerations available to planners in new construction, such as facility siting, landscaping, and facility access. The final definition of a "renovated facility" would be "a previously existing facility that has been retrofitted within the confines of the existing structure without increasing the existing living and working space; includes all work and materials necessary to improve the existing facility and provide a complete and usable facility."

Effective Use

The definition of "effective use" is the most problematic of all the definitions, but the most important aspect to define in regards to analysis of blast mitigation materials and methodologies. The whole crux of the thesis is to look at the armed services' attempts to incorporate innovations in materials and methodologies for blast mitigation and make some sort of a determination to what extent this incorporation has occurred, and whether or not the extent is considered adequate. This seems to be very subjective, and rightly so. However, in order to be able to answer the thesis question, a scale needs to be implied to provide an answer that, while subjective, is still quantitative. For purposes of this analysis, effective use will entail that the armed services are aware of the innovation (either by direct testing, indirect testing, or review of third party results), have made some judgment on whether or not it is applicable for incorporation, and have taken the steps or are in the process of taking the steps necessary to facilitate its use within present and future projects. How and what factors are used to make this judgment call will not be examined in this analysis, and would make a good topic for future research and analysis.

Defining the Threat

Although discussed earlier in the thesis, a re-look at the threat being addressed by the innovations discussed is in order. The scope of this analysis is limited to threats posed by vehicle bombs, IEDs and other traditionally nonmilitary type applications with the exception of RPGs. The assumption is that personnel delivered devices pose the threat, by hand or by vehicle, rather than military vehicle delivered munitions (heavy artillery, tank rounds, air-delivered munitions, guided missiles, and other munitions). The threat addressed is from nonstate actors, acting in small groups, who in all probability do not have access to or the ability to covertly deliver munitions such as missiles, penetrating weapons, or antiarmor military munitions.

The Current List of Innovations in Materials and Methodologies

The entrepreneurial spirit alive in the world today has shouldered a large part of the responsibility of divining and developing innovative materials and their application in blast mitigation. While the governments of the US (and the rest of the world) may have provided the initiative by stimulating the development of these new technologies, it has been the grunt work done in the private sector that has furthered the development of technologies designed to minimize the effects on facilities as a result of a localized explosion. While the innovations and their derivatives are too numerous to mention in their entirety, they can be discussed and analyzed as a group of like innovations, highlighting the applicability and singling out specific innovations worthy of note. For purposes of this analysis, the innovations will be broken down first into materials and methodologies, further divided into specified classes, and then examined with respect to both new construction and renovation applications.

Innovations in Blast Mitigation Materials: Bricks and Sticks

Materials are simply defined as the raw products used in a construction or renovation project. Blast mitigation effectiveness for a material innovation is based on the composition and inherent qualities of the material itself, not necessarily how the material is used. To better describe this, an example may be in order: a material innovation in building structural framework may be to make the members stronger, less susceptible to shearing force, and more flexible to better absorb the blast wave pressure. In contrast, a nonmaterial innovation in building structural framework would be improving the design of how the members are fit together to provide a design structure capable of resisting a higher level of blast force. To examine the material innovations, primary categories were derived that encompassed the vast majority of the existing innovations in the public and private sector. These categories include: doors, windows, curtains, wall materials, applied coatings, and exterior structures.

The doors category is just that: material improvements in the construction of exterior and interior doors to better survive the overpressures of a localized explosion. Tests and investigations of actual explosions have shown doors and windows as weak spots into a structure, and the cause of indirect damage to the facility and personnel occupying the facility during an explosion. Simply put, by improving the door to resist blast overpressure and reducing the indirect damage caused by ordinary doors, the entire facility is improved in its ability to absorb the blast and minimize damage. Doors have been the focus of both improvements in construction and renovation projects, to an almost identical extent, since a door can be changed as part of a renovation project almost as easily as it can be installed in a new construction project. The US Air Force has looked at improvement in the construction of doors in multiple test sets and experiments. Recent research at the Air Force Research Laboratory (AFRL) has made significant strides in addressing the retrofit of older, less resistant doors with doors that are lightweight yet still resistant to explosive blast effects (Anderson and Dover, Lightweight Blast Resistant Doors, 2003). Their work epitomizes the work done in the commercial sector: it has focused on three aspects of blast resistant doors: first, they must be lightweight; second, they must be capable of withstanding a specified blast pressure; and third, the frame must be capable of holding the blast resistant door. One of the products reviewed by the AFRL was the Accordion-Flex door, which consists of a metal door constructed like an accordion with folds and a solid frame that can expand to absorb the pressure generated from a nearby explosion (Anderson and Dover, Lightweight Blast Resistant Doors, 2003). Other products are currently being marketed that utilize steel reinforcement members and specially designed doorjamb and mounting hardware to increase the door's ability to resist blast forces. Examples of these commercially available doors include Overly Door Company's pre-engineered blast doors (Overly Door Company 2004) and Krieger pre-engineered blast and pressure doors (Krieger Specialty Products 2005). Whether for construction or for renovation, innovations in door construction have focused on strengthening the door against blast pressure and strengthening the doorjamb and hardware to contain the door without sacrificing aesthetics and ease of opening.

Windows are similar to doors with respect to blast mitigation in that they represent weak points into a structure; an anomaly in a smooth exterior wall for the blast overpressure wave to exploit in the event of a detonation. Also similar to doors, windows can for the most part be just as easily replaced during a renovation project as they can be placed during a construction project. So, for all intents and purposes, there is little difference between windows as part of construction versus renovation blast mitigation. Where windows are distinguishable from doors is in the materials used and the options that can be employed to strengthen a window. Unlike a door, a window does not offer the same extent of hidden or unseen places to arraign strengthening members or other structural framework. Since the obvious use of a window is to provide unobstructed view to the outside and the passage of natural light into a facility, the window must maintain at least a portion of its unhampered visibility. Also, untreated glass is a very brittle medium that cannot absorb much pressure and still remain intact. Therefore, to produce a more blast resistant window that maintains the passage of light and yet minimizes the indirect damage during a blast event to occupants and property as a result of broken glass, the focus must be on improving the window's ability to absorb pressure and minimizing the breakage effects of natural glass. There is been a voluminous amount of research and development done to design windows that can withstand a blast wave. One noticeable study was the Divine Buffalo series of tests conducted by the Defense Threat Reduction Agency (DTRA) in the 1990s. One of these tests, series number 9, subjected a group of windows to the air blast produced by a 5,000 pound explosive charge to determine the results of different window types, retrofit safety films and window treatments. A total of 49 different windows were tested with variations such as annealed and tempered or toughened glass, laminated glass sheets, single and double paned, dry- and wet-glazed mounting, and antishatter film (ASF) (Plamondon and Sheffield 1999, 10-12). Basically, these different aspects all represent some of the myriad of options available to strengthen glass windows. Other window innovations include flex mounting which utilizes double pane glass with ASF mounted in a flexible frame complete with dampening chambers to vent the air between the panes (Anderson and Dover, Sealed Blast-Resistant Windows 2003). In another improvement similar to laminating, the glass itself can be augmented with polycarbonate glazings and coatings and tied directly into the wall, slab, and ceiling for additional strength (Coltharp and Hall 2003, 33). While seemingly expansive, this is but a small number of the various iterations of improvements to windows that are being made to increase their resistance to blast pressures and that can be applied to both construction and renovation applications.

Curtains are related to windows, but different enough to warrant their own category when examining blast resistant materials. One primary reason: they are extremely cost effective and easy to install as part of a renovation program. Basically, the curtain is a simple device: a window covering that is not an integral part of the window, but improves the overall resistance to blast effects. The curtains can be constructed from a variety of materials, including warp knit fabric or polyethylene fiber. The entire system consists of the curtains themselves, the attachment mechanism used to secure the curtain to the interior window frame and a separate attachment to hold the bottom of the curtain and the extra material of the curtain (Smilowitz 2003). The intent of the curtain is to prevent any broken pieces of glass from entering a room; during a blast event, the glass is blown inward into the room, the curtain catches the glass and directs it downward, and the glass collects on the floor at the base of the window. The curtain, while able to be removed or opened, is intended to remain shut and secured at all time to be effective. Leaving the curtain open negates the protection offered by the system. This is a definite design consideration, because the curtain dramatically changes the appearance of the window and, depending on the color and type of material used, can degrade the amount of light that can pass through the window. Where the curtains can be most effective is in situations where a temporary fix is required or where cost is an overriding concern. The low cost and relative ease of installation of blast curtains makes them a useful tool during renovations when the budget is extremely tight. While the aesthetics may suffer somewhat as a result, the amount of protection afforded per unit cost is especially high. In addition, the curtains could easily be removed at a later date and the window replaced with a more aesthetically pleasing system, one that incorporates such blast mitigation features such as ASF, laminated glass, and flexible mounting attachments. This same scheme would work in a facility where the windows are scheduled to be replaced in a future fiscal year or which will be vacated at some future point and is no longer receiving long term investments. The curtains could provide the increased level of protection until the new windows are installed or until the facility is no longer required.

While doors and windows may be the weaknesses of buildings with respect to blast effects, it is important to not overlook the walls themselves when it comes to blast mitigation. Ensuring that the walls of the facilities possess the maximum amount of blast resistance is crucial to the comprehensive blast mitigation program. Walls are most typically strengthened during construction projects, due to the difficulties of changing the wall composition during a renovation project. New developments and improvements by the US Army Engineer Research and Development Center (ERDC) in concrete have yielded what is referred to as Very-High-Strength concrete, which can be extremely effective in new construction projects in maximizing blast resistance potential (Cargile, O’Neil, and Neeley 2003, 61). Concrete is a very economical and effective building product: available almost universally, relatively easy to work with, and flexible for a large number of applications. However, in order to be effective in blast mitigation, conventional concretes must be poured to a thickness that exceeds economical and aesthetic factors. ERDC has furthered research to develop concretes that, through the use of specialized aggregates, chemical mixtures, and pressure treatments, can be effective blast mitigation agents. Another innovation is the use of cold-formed steel studs to reinforce infill wall systems. Infill wall systems are walls constructed with reinforced concrete or steel frames, and then in-filled with unreinforced concrete or masonry. While capable of withstanding wind loads, these types of walls are not capable of withstanding blast loads. Steel stud walls can be constructed inside the existing exterior walls or retrofitted into the infill area. By properly determining ductile performance and securing the steel studs into the existing framework, the wall is made capable of withstanding large deformations from blast effects, but still maintaining load carrying capability (Salim et al. 2003). Finally, existing walls that contain hollow spaces, such as concrete block or interior stud and wallboard walls can be spray-filled with polymer foams that expand to fill the hollow space and enhance the wall's ability to absorb energy without fragmenting (Lane, Craig, and Babcock 2004, 39). By utilizing these improvements to wall materials, new walls can be built that have maximum blast resistance potential, and some existing walls can be strengthened internally to meet minimal levels of resistance. For those existing walls where it is not feasible to replace or improve the materials of the walls themselves, there are ways to augment the existing walls to provide maximum blast protection.

Another category of materials is the applied coatings which are normally applied to exterior or interior walls in order to augment the wall's ability to resist blast effects. These coatings may also be applied in other areas, such as doors and ceiling materials in order to reduce the indirect damage to the facility and occupants from ejected material resulting from a blast. The AFRL has conducted successful tests using elastometric polymer materials sprayed onto lightweight structural components such as concrete block walls and interior wall surfaces (Knox et al. 2001, 1). These polymer materials are close cousins to the material that is used for concrete floor coverings and truck bed liners. While the applied coating does not improve the structural strength of the material it is applied to, the elastic properties of the applied coating allow a large degree of deformation while still containing the debris normally associated with the blast effect on the base material. The effect is enhanced if the coating can be tied into the surrounding structural members (floor joists, ceiling joists, and other structural components). These materials are primarily useful for retrofit and renovation, since the material is easy to apply, cures very quickly, and can introduce a significant level of ductility and resilience into at risk wall systems (Porter et al. 2003, 47).

The final category of blast mitigation materials is the exterior structures. This category is in a gray area between being considered as a material or a methodology, but for purposes of this analysis will be considered a material innovation. The exterior structure category includes those improvements outside of the facility itself that provide additional blast resistance potential to the facility. As they are exterior to the facility, they can be included and utilized both in new construction projects and in renovation projects. The primary considerations for using these types of improvements are economical and aesthetical. One example would be a reinforced blast wall constructed of blast resistant concrete and backstopped with an earthen berm. While effective, the addition of a twelve foot concrete wall around the facility may not be pleasing to the eye, or present the type of appearance that the occupants would like to reflect. However, through the clever use of materials and architectural design, the exterior structures could actually enhance the appearance of the facility. A secondary wall built against the existing wall could be blended into the appearance of the facility, giving the facility the look of a “face-lift” while adding additional blast resistance. Specially engineered improvements to the exterior of the facility could reflect blast waves away from the more vulnerable sections of a facility. While not one of the most robust categories of blast resistant materials, the exterior structures can be used in addition with other materials and methodologies to produce an effective overall blast mitigation effect.

Innovations in Methodologies: Better Protection through Better Methods

As opposed to materials, innovations in methodologies represent those improvements made as a result of changes to the way materials are used, rather than the materials themselves. While in some cases there is a fine line on what is considered material and what is considered nonmaterial, this analysis will focus on a group of specific methodologies that incorporate the majority of innovations. These categories include design considerations, blast redirection, and energy absorption.

Design considerations are by far the largest and most complicated methodology that is employed in improving a facility's resistance to blast energy. So much so, that a comprehensive analysis of design considerations could be (and has been) a separate series of thesis analyses by itself. This category is analogous to preventative medicine: the more aspects considered and addressed during the design phase, the less risk in the occupied stage. Design considerations as a whole cannot be considered innovations, since facility designs have been considered since man built his first structure. However, what is considered innovative is the change of focus from aesthetics and convenience as primary considerations to secondary considerations, with protection and control becoming primary. This analysis will color design considerations with a wide brush, giving an overview of the blast mitigation considerations that fall under the category rather than a comprehensive analysis of all design considerations. Design considerations can be subdivided into two subcategories for ease in analysis, exterior and interior.

Outside considerations, otherwise known as exterior or site level consideration focuses on the areas around the facility to be protected, focusing on land use, site selection, facility orientation, vehicle access, control points, physical barriers, landscaping, parking, and protection of utilities (FEMA, Primer for Design of Commercial Buildings to Mitigate Terrorist Attacks 2003, 6.1-7). While most of these considerations pertain to new construction facilities, they can be used to limited extent for renovation facilities as well. Outside considerations deal primarily with positioning the facility to minimize accessibility and applicability of blast agents and providing access to the facility by occupants and discouraging access by potential terrorists and saboteurs. Since this analysis is focusing primarily on the technical considerations of blast mitigation, the area of concentration will be on physical aspects (landscaping, siting, and other physical aspects) rather than security aspects (such as check and control points, exclusive zones, and other nonmaterial aspects).

Inside or interior considerations are those considerations in and of the facility itself, which includes strengthening the facilities structural systems, minimizing flying debris, hardening the exterior of the facility from the inside, as well as optimizing the facility for potential future evacuation, rescue, and recovery efforts (FEMA, Primer for Design of Commercial Buildings to Mitigate Terrorist Attacks 2003, 6.35). A comprehensive approach would consider the building configuration, use of space, redundancy of key systems, ductile (flexible) structural elements, loads and stresses, material in construction use, roof design, and other considerations.

Blast redirection, in a sense, could be considered as a design consideration as well. But since it incorporates more than just strictly design, it is considered as a separate category. Blast redirection is a methodology that uses materials, design, and placement techniques in order to redirect the energy from a blast away from a facility's vulnerable areas. A blast event creates a pressure wave, which expands away from the source of the blast outward. In a perfect void, the blast would radiate outward in a perfect sphere. In the real world, the wave is blocked and directed by obstructions. The key to blast redirection is to control that process of blocking and direction by obstruction away or around the facility being protected. The approach is very situation dependent; each facility, either being newly constructed or renovated, needs to be considered as a separate system. Factors to be considered include threat level, avenues of approach, most likely scenarios, most likely location of blast event, terrain, foliage, building design considerations, building construction materials, facility critical vulnerabilities, and a number of other factors. Computer simulation software can be very helpful during this consideration through construction of a specific model for the facility. This analysis can show the most likely pattern of blast waves and how they affect the facility. Using this information, the terrain and the facility itself can be altered to redirect the pattern of blast waves in a way that would focus the minimum amount of blast energy on the facility. Alterations can include the addition of exterior structures (walls, substructures, and other external features), landscaping features, building protrusions, movement of windows and doors to less exposed areas, relocation of vehicle access routes and parking, and others. Blast redirection can and should be considered during the design of new construction facilities, and can be used to assess and upgrade renovation facilities. Since the effectiveness of this methodology is situational dependent, it is best utilized as a part of a comprehensive blast mitigation analysis and improvement program.

Energy absorption is similar in some respects to blast redirection, but focuses on the ability of the facility to absorb energy with minimal disruption rather than redirecting the energy elsewhere. Again, this is another category that could almost be considered a material category, but this analysis will focus on the improving the ability of the entire facility to absorb energy, rather than the individual materials that are available. As with blast redirection, a comprehensive study of the facility is required to determine areas of the facility most likely to sustain destructive level blast energy. These areas are modified in order to improve their ability to absorb energy. The majority of modifications to improve ability to absorb energy are material changes, such as the window and door replacements listed in the materials sections. Other ways of improving energy absorption would be to provide an absorbing obstruction, such as an entryway in front of a main door constructed to blunt the blast wave prior to hitting the main door. Energy absorption is a methodology that is also best applied as part of a comprehensive study of an entire facility, used to supplement and enhance other material and methodology innovations.

Expertise in Blast Mitigation: Who Does This the Best?

Terrorism is an international concern and while the US has increased focus in the last ten years or so, the international community in some particular areas has been dealing with it for a lot longer. Israel, Lebanon, South Africa, Ireland, Germany, and other countries or areas have had more than their share of terrorist bombings and therefore have had to focus on mitigating the blast effects of terrorist weapons for some time. While these other countries have been dealing with the problem a lot longer, the US is out in front when it comes to writing doctrine, guidance, and standards for formalizing focus on blast mitigation in facility construction and renovation. This view may be speculative on at least two issues. First, the preponderance of information on the Internet is from US government, educational, or industrial sources. This could be because the US is a leader in blast mitigation technology and application, but may be also a factor of prevalence of Internet access available to US corporations, educational institutions, and government offices. Second, the capitalistic nature of the US economic system stimulates the amount of information available to the researcher on a particular subject. In other words, the quasi-private company exclusively selling blast mitigation construction material to its foreign government partner has no need to advertise and publish findings; this does not detract from their ability and expertise in blast mitigation techniques, but makes it much more difficult for the researcher to qualify and validate. That being said, there are a number of international players, primarily on the private sector side, that contribute their expertise and research to blast mitigation innovations.

Testing, Assessing, and Validating Blast Mitigation Materials and Methodologies

In order to discover, recognize, and judge the effectiveness of various blast mitigation materials and methodologies, testing and analysis of results is required. Testing is accomplished either within the services, within other government agencies, or under sanctioned contract to qualified private sector companies or organizations. Testing is done under specified conditions, in order to replicate the actual conditions that the material or methodology being tested would be subjected to during an actual blast event. In order to best understand how a test is set up and executed, a case study will be detailed as an example to the process. The case under consideration is the Divine Buffalo 9 Test Event, executed in February 1999 by DTRA at the Intermediate Test Bed of the DTRA

Permanent High Explosive Test Site, located at the US Army White Sands Missile Range, New Mexico.

Testing in the Armed Services and Other Government Agencies

Within the armed services, the Air Force uses their own Air Force Research Laboratory, which has multiple locations dedicated to specific functional areas. Blast mitigation testing is usually done at Tyndall Air Force Base (AFB), Florida. The Army has the US Army Engineer Research and Development Center; blast mitigation testing is done at the Geodynamics Research Facility. The Navy has the Naval Facilities Engineering Service Center; blast mitigation testing is done at Port Hueneme, California. In addition, there are a host of other government organizations that conduct their own blast testing, either with their own facilities or contracted out to a number of qualified contractors. For example, the DOS maintains its own testing sites at Eglin AFB, Florida, and routinely shares the information it obtains during testing with all the other government organizations (Ashbery 2001, 5, 6-7). In fact, there is a Technical Support Working Group (TSWG), which was established to share information among all the government organizations related to a host of national defense technical issues, including blast mitigation. Members include the DOS, DOD, Department of Homeland Security (DHS), and Department of Energy (DOE), plus the Federal Bureau of Investigation (FBI), Central Intelligence Agency (CIA), Bureau of Alcohol, Tobacco, and Firearms (ATF), Secret Service, Federal Aviation Administration (FAA), and other organizations. Also, international partners are involved, including Great Britain, Canada, and Israel (Technical Support Working Group 2004, 3). From distribution lists observed in multiple testing results, it appears that all members of the TSWG do an admirable job of ensuring that test results and other important information is distributed widely and to all members routinely.

Case Study: The Divine Buffalo 9 Test Event

The Divine Buffalo 9 Test Event was conducted by DTRA (via a support contract with Applied Research Associates, Inc.) in February 1999 to test various types of windows, concrete masonry unit (CMU) walls, and a five minute force protection wall. All information in this case study came from the official project officer's report (Plamondon and Sheffield 1999). The test was conducted for the TSWG as part of an effort to coordinate as well as sponsor interagency antiterrorism (AT) research and development. The intent was to simulate a high explosive detonation near an urban office building. As with most TSWG tests, multiple experiments from multiple agencies were combined on a single full scale test structure to be both cost effective and to allow distribution of results through all applicable and interested agencies.

The test was set up to maximize the use of a single blast, which was designed to approximate a large vehicle delivered explosive device. The explosive device consisted of a hemispherical stack of composition 4 (C-4 plastic explosive) bricks with an explosive potential of approximately 5,000 pounds. The bricks were stacked on a wooden table that was approximately three feet above ground level. The C-4 was detonated from the center of the stack. This setup was roughly similar to the explosive devices used at the Alfred P. Murrah Federal Building in Oklahoma City and the Khobar Towers barracks. The charge was located approximately 150 meters (492 feet) from the south side of the testing facility.

The testing facility used was a four story reinforced concrete structure. The windows to be tested were mounted on the south face of the second, third, and fourth floor of the facility, while the two CMU walls and the force protection wall were located on the first floor. The building is divided into individual cubicles, basically one cubicle per window. Each floor (second through fourth) had 14 windows, for a total of 42 windows. In addition, six reinforced concrete cubicles were also used, at a much closer range: two cubicles were located at 46 meters (151 feet) and the other four were located at 60 meters (197 feet). In total, 49 windows and 3 walls were exposed to blast effects.

The windows to be tested were a mixture of different types, thicknesses, frames, and mounting details. In addition, some had safety film applied and some used bomb blast net (BBN). Each window had a different configuration, in order to produce the most complete and comprehensive test results. The different types of window glass used were: annealed, tempered or toughened, and laminated. The thickness of the glass varied from 4 to 19 millimeters. The size of each window was roughly 1.3x1.6 meters (4.3x5.4 feet). Both single pane and double pane windows were tested; there were 10 double paned windows with a 12 millimeter air gap and 39 single paned windows. Mounting options included either a dry-glazed (neoprene gasket) or wet-glazed (Arbokol 2000 sealant and neoprene gasket) mount. ASF was applied to 22 windows, three windows had BBN curtains installed, four windows had catcher bars, one had a five minute forced entry grill, and one had a blast shield installed. All in all, the different windows provided a large group of different options and configurations for a comprehensive set of results.

Of the three walls to be tested, the first was a five minute force protection wall. The wall consisted of 14 gauge, 2x6 inch steel studs on 16 inch centers covered by 1x6 inch planks and topped with a 6 gauge steel plate. The other two walls were CMU walls, 8 inches thick, filled with grout and braced by anchors at the top and the bottom. These two walls were primarily control walls to provide control data for the experiment.

The blast itself created a crater in the ground approximately 30 feet in diameter and 9 feet deep. Without getting into the details of the measurements, pressure variations, individual response and results at each window or wall, and other technical data, the tests were deemed to be a success. The results summary is as follows:

1. Single paned windows created a high hazard environment (HHE) in 70 percent of the tests
    a. Application of ASF did not prevent the HHE
    b. Curtains, catcher bars, and the frame guard systems were effective
2. Single paned tempered or toughened windows created HHE in 50 percent of the tests
    a. Tempered glass was less effective than toughened glass
    b. ASF was effective for large chunks of glass
3. Double paned windows created HHE in 10 percent of the tests
    a. Only the thinnest (4 millimeter) window created HHE
4. The five minute force protection wall was still standing, but was partially pulled from its anchoring

Test results were distributed widely, to the Defense Advanced Research Projects Agency (DARPA), DTRA, Defense Technical Information Center (DTIC), Joint Warfare Analysis Center (JWAC), Office of Special Technology (OST), Department of the Army, Department of the Navy, Department of the Air Force, DOE, CIA, DOS, FAA, FBI, National Security Agency (NSA), Security Police Board, US Secret Service, and a group of government contractors (ARA, Logicon, SAIC, TRW, and others).

Changes to Construction and Renovation Standards

Research, development, and testing are definitely important, but execution is where the rubber meets the road. In order to be able to execute, or to utilize, these modern innovations in blast mitigation innovations, the foundation has to be set into standards, criteria, design guides, and all the other documentation that drives the construction and renovation processes. For continuity's sake, there needs to be some sort of common reference document applicable to all the services, which exists in the *Unified Facilities Criteria: DOD Minimum Antiterrorism Standards for Buildings*. This document provides the floor level standards that are required of all the services in the DOD. However, the documentation does not just stop there. Each service has some sort of documentation, in the form of additional criteria, design guides, or other similarly named set of standards that further refines and enunciates the vision of the individual service. Finally, there are some other government organizations that have crafted their own standards and criteria for federal government buildings. This remains applicable to the armed services as well, primarily due to the fact that some service members are attached to geographically separated units that may be located in federal buildings around the world, buildings that are constructed under standards and criteria different than the Unified Facilities Criteria (UFC). While not necessarily less restrictive than the DOD standards, it behooves the individual to understand to what standard the facilities has been constructed under when gauging the risk of potential blast events.

Baseline: DOD Minimum Antiterrorism Standards for Buildings

For obvious reasons, the DOD has always had an interest in reducing the effects of blast events on facilities. Granted, prior to the 1950s this was primarily about wartime scenarios and the use of contingency methodology to strengthen unit facilities in the field of battle. However, during the beginnings of the nuclear age, the military began to focus not only on blast effects in the field, but blast effects on permanent facilities that may be located within the US. During that time, the services joined together to produce TM 5-1300, “Structures to Resist the Effects of Accidental Explosions,” which for 30 years was the standard for predicting explosive effects and thereby the key to designing facilities that could withstand prescribed blast effects (Lindsey 2003, 17). After the bombing of Beirut in 1983, the DOD tasked the Army to develop procedures to prevent this type of event from occurring again. The Army formed the USACE Protective Design Center (PDC), which created the “Security Engineering Manual” to address this concern. This morphed into the TM 5-853 series of manuals: “Security Engineering Project Development,” “Security Engineering Concept Design,” “Security Engineering Final Design,” and “Security Engineering Electronic Security Systems” which were published in 1994 (Lindsey 2003, 18).

After the Khobar Towers bombing in 1996, the DOD refocused on protecting personnel from terrorist bombing attacks and tasked the USACE PDC to establish a DOD wide team to put together the initial draft of the DOD AT standard *Interim Antiterrorism (AT)/ Force Protection (FP) Construction Standards.* The team continued to work on the standards, involving outside agencies such as the General Services Administration (GSA) and DOS. The final draft was published for coordination in August 2001, completed in

December 2001, revised as a UFC in May 2002, republished for coordination in June 2002, and finally published as UFC 4-010-01, *Unified Facilities Criteria: DOD Minimum Antiterrorism Standards for Buildings* (Bradshaw 2003, 11-12).

The main goal of UFC 4-010-01 is to increase survival rates in buildings targeted by terrorists. The standards attempt to accomplish this by describing an overarching strategy with five guiding principles: Maximize standoff distance, prevent building collapse, minimize hazardous flying debris, limit airborne contamination, and provide mass notification (Bradshaw 2003, 12). Specifically, there are 23 standards for new construction and renovations that are outlined as a means of providing protection to occupants regardless of the type of terrorist threat. The standards are listed in appendix A. In addition to the standards, there are 16 additional recommendations for new construction and renovation projects, which are listed in appendix B. Having a common set of standards puts all the services on the same footing, and provides an easy to follow, easy to understand set of criteria that, if implemented into new construction and renovations projects, will provide a satisfactory level of protection for facility occupants.

Service Specific Guidance and Criteria

Even with the overarching guidance provided by the UFC, the individual services have seen fit to develop service specific documentation that helps to define their specific needs, or directs more demanding criteria than that provided by the DOD. While there are a multitude of documents which either specify or reference blast mitigation, this analysis has examined a subset of documents to provide an overview of the type of documents that are available. As with any specific project, research should be done prior to undertaking the project to ensure that all applicable criteria and standards have been identified and conformed with.

The Air Force has issued a guide for blast mitigation from the Air Force Force Protection Battlelab entitled *Vehicle Bomb Mitigation Guide*. What is unique about this particular guide is that it is printed as a top bound, pocket sized tablet, suitable for storing and carrying in the hip pocket of the battle dress uniform. Handy, since the document has a lot of information in it applicable to the warfighter, in terms of both procedures and materials. However, it also has applicability to the permanent facility designer as well. The document provided information about blast events and the forces associated with them that could affect a facility. This includes multiple charts showing weapon types versus environmental aspects to estimate anticipated damage to facilities. The document also discusses the threat, expanding upon how vehicles are used as potential weapons and the types of explosives that are used in this manner.

The Navy has developed multiple documents as well addressing design considerations and criteria when striving to mitigate the effects of blast events. One such document is a technical report entitled *Protection Against Blast Effects From Terrorist Vehicle Bombs*. The document was more or less intended for security specialists rather than engineers, but can be used by either to make an initial assessment of a facility to determine its potential ability to withstand the effects of a blast event (Ferritto 1997, 3). The document is similar to the Air Force pamphlet in that its approach is not only to advise but to educate. The document walks the user through the different forces involved in a vehicle-borne blast event, discussing different examples and showing estimations of certain devices and materials detonated at differing distances to structures. The document also discusses the effects on different building materials, and then follows with strategies on how to minimize damage to the facility and to the occupants inside. This document would be very useful in the same situation as the Air Force pamphlet, as a guide to help identify facilities at risk and roughly calculate the level of that risk.

Another Navy document, *User's Guide on Protection Against Terrorist Vehicle Bombs* is similar to the first document, but focuses more on the engineering aspects of design and materials for blast mitigation. The purpose of the document is to define an easy to follow facility design process, provide sufficient criteria to support the analysis process, and to provide examples on the use of the criteria (Naval Facilities Engineering Service Center 1998, 2-1). The design process is outlined in flow chart fashion, with included text, to provide the user with a simple but effective system for determining the level of threat, the level of protection required, and the methodology for improving current conditions to achieve that level of protection. The guide also contains calculations to back up the decisions made in the flowchart models, allowing the user to scale and adapt as required to meet the specific facility under consideration. Finally, the document discusses vehicle barriers, fragment retention film, blast curtains, shades, spall shields, and glazing systems in detail in order to assist the user in utilizing these specific innovations in both new construction and renovation projects.

Criteria and Guidance Established by Other Federal Agencies

Other federal agencies have also determined the need to focus on their own facilities as well, due to the increased threat of a potential terrorist blast event. Unfortunately, it usually takes some sort of shock to generate change, and the various federal agencies were not immune to that need for stimulus. For the majority of federal agencies (not including the DOS and the DOD), the WTC bombing in 1993, from a point of policy change and transformation, was an anomaly; not a stimulus for change (see Figure 4). The stimulus came from the bombing of the Alfred P. Murrah Federal Building in 1995. Now, in this case, the Department of Justice (DOJ) was presented with an all-too-clear vision of required change in the ability of their facilities to absorb and deflect the forces of a terrorist blast event. Literally the day after the event, the President directed the DOJ to assess the vulnerability of federal facilities in the US to similar acts of violence (Smith 2003, 3). The ball was handed to the GSA, who formed a committee including members from the DOJ, the US Marshal's Office, GSA, DOS, Social Security Administration, and DOD to examine these vulnerabilities. The final product of this committee was a report entitled *Vulnerability Assessment of Federal Facilities*, dated 28 June 1995. The report had some insightful conclusions, such as the need to protect occupants from the hazard of flying glass (through some sort of shatter resistant material), the need to establish uniform construction standards, the need to form a federal government oversight committee to address government security concerns (later titled the Interagency Security Committee), and the need to do a review of the risk assessment methodology in place prior to the Oklahoma City bombing (Smith 2003, 3-4).

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Figure 4. Underground parking garage, World Trade Center, February 1993
Source: Laurie Mylroie, "Iraqi Complicity in the World Trade Center Bombing and Beyond," *Middle East Intelligence Bulletin;* available from http://www.meib.org/articles/0106_ir1.htm; Internet; accessed 11 October 2004.

The GSA took the results of this report one step further and used its recommendations to draft a set of design criteria addressing security concerns, appropriately entitled *GSA Security Criteria,* which was released in draft format in October 1997. What was significant about this document was that it required a different vision than that currently available as reference, namely the standards at use for DOD and State facilities. The federal buildings being addressed were not secured facilities, but facilities open to the general public and intended for high traffic levels of civilian access. GSA presented its draft criteria to the Interagency Security Committee (ISC) for review and applicability to all federal agencies. The criteria were eventually adopted on May 2001 by all 26 member agencies of the ISC and were officially titled *ISC Security Design*

Criteria for New Federal Buildings and Major Modernization Projects. The criteria are applicable to all new construction of facilities not under jurisdiction or control of the DOD. The criteria also does not apply to airports, prisons, hospitals, clinics, border patrol stations, ports of entry, or unique facilities such as the Pentagon or CIA headquarters (Smith 2003, 5).

The DOS, like the DOD, had been exposed to the potential of terrorist blast events for a significantly longer amount of time than the other agencies. This was primarily due to the various bombings and bombing attempts that had occurred at multiple embassy sites. The keystone event for the DOS was the bombing of the embassy and Marine barracks in Beirut, Lebanon in 1983 (see Figure 5). At that time, the DOS undertook the Inman Project, which was intended to develop criteria for new construction and renovation of DOS facilities to upgrade security and blast mitigation properties. The DOS program got additional momentum after the bombings at the US embassies in Kenya and Tanzania in 1998 (see Figure 6), which resulted in their current criteria, a five volume set of criteria known as *Architectural & Engineering Design Guidelines for US Diplomatic Mission Buildings* (Smith 2003, 6).

Figure 5. Marine Battalion Landing Team Barracks, Beirut, Lebanon, October 1983
Source: "US Multinational Force [USMNF] Lebanon," *GlobalSecurity.org;* available from http://www.globalsecurity.org/military/ops/usmnf.htm; Internet; accessed 10 March 2005.

The FAA has responsibility for the airports and other facilities that support the National Airspace System. The FAA developed their own criteria, *FAA Order 1600.69 – FAA Facility Security Management Program,* which is very close to the ISC/GSA standard, but specifies a larger explosive threat size (Smith 2003, 7). This document is available for official use only and was not made directly available to the researcher.

Another couple of interesting policy and criteria documents have come from the new DHS, particularly out of the Federal Emergency Management Agency (FEMA). Two publications are of particular note, although they also publish other documents that cover different aspects of protection. The two documents are the *Primer for Design of Commercial Buildings to Mitigate Terrorist Attacks* and the *Reference Manual to*

Mitigate Potential Terrorist Attacks Against Buildings. Both of these documents were published in 2003, after being commissioned by the DHS as a result of the 11 September 2001 attacks at the WTC and the Pentagon. Although these are government published documents, the intended audience is state and local governments, as well as the commercial sector. The intent is to provide those organizations viable criteria to use for blast mitigation (among other security concerns) efforts in new and renovated facilities.

Figure 6. Bombing of the US Embassy, Nairobi, Kenya, 7 August 1998
Source: "1998 U.S. embassy bombings," *Wikipedia: The Free Encyclopedia;* available from http://en.wikipedia.org/wiki/1998 U.S. embassy bombings; Internet; accessed 8 March 2005.

The Future of Blast Mitigation Innovations

One aspect of effectiveness that has not been discussed is the factor of time. Time causes all things to evolve, and blast mitigation techniques are not immune from this inexorable process. As the threat evolves and changes, so should the protection technology and application methodologies. New materials will be developed, new applications of old materials will be discovered, and both evolutionary and revolutionary changes will occur in the nature of this particular brand of warfare. Consequently, to remain effective, the use of future innovations in blast mitigation must also continue to evolve. While it is difficult to predict future technology changes (except for perhaps some near future evolutionary changes), it is easier to predict the organizational and doctrinal changes that may occur in the future that could impact the use of blast mitigation in future construction and renovation projects.

Material Changes: Transparent Aluminum and Other Innovations

Loyal Star Trek fans will recall the part of the movie "Star Trek IV: The Voyage Home" where after a trip back in time Chief Engineer Montgomery "Scotty" Scott is tasked with building a tank to transport whales, and passes a not-yet-invented recipe for transparent aluminum along to a perplexed current-day Plexiglas manufacturer (Bourne 2003). While fictitious, what was shown here was an evolutionary shift in material technology: a clear, lighter, stronger version of a previously existing material. Since 1993, there have been similar evolutionary changes in materials, such as very-high-strength concrete, polymer coatings, and ASF for example. It is reasonable to expect that changes and improvements will continue to occur in the years to come.

New materials will continue to be discovered that can be utilized eventually in blast mitigation programs. The armed forces are taking an active role in working to discover new technologies that can augment and improve their ability to protect facilities from blast effects. The primary method for pursuing new materials is by encouraging production in the private sector. The DOD, working in conjunction with the University of California at San Bernardino, is offering grants to successful applicants to encourage product development in a number of key military and homeland defense needs, to include (among others) blast mitigation, detection of IEDs, protective metal coatings, and advanced smart materials, all of which may play a roll in future blast mitigation programs (Jackson 2004). The armed services also do research at their own laboratories as well, although the research usually involves testing already existing innovations rather than developing new and unique products. The Air Force has the Air Force Research Laboratory, which has multiple locations. Blast mitigation testing is usually done at Tyndall AFB, Florida. The Army has the US Army Engineer Research and Development Center; blast mitigation testing is done at the Geodynamics Research Facility. The Navy has the Naval Facilities Engineering Service Center; blast mitigation testing is done at Port Hueneme, California.

Production methods will also play a part in the development of materials for blast mitigation purposes. There are currently in existence materials that may be applicable for blast mitigation from a technical standpoint, but are not suitable for industrial or economical reasons. As an example, consider the lowly spider web, particularly from the Nephila Clavipes spider. Researchers determined a number of years ago that spider web, when woven into a fabric, looks and feels like silk but possesses the elasticity of nylon and thirty times the strength of Kevlar. From a technical point of view, this makes it a strong candidate for inclusion in blast mitigation programs. However, it is extremely difficult and expensive to gather and weave the web into a usable fabric, involving large amounts of time and requiring weaving by hand. However, in 2004, researchers at Carpo

Nove were able to assembly line the process by genetically producing a superior web producing spider and by designing state of the art techniques that allow all work to be done by machines instead of by hand, drastically reducing the cost and setting the stage for mass production of spider web fabric (Grado Zero Espace 2004). Similar discoveries on how to produce materials quicker and more economically will result in additional materials suitable for use in blast mitigation programs.

Technology Transfer: Continuity Between the Players

The future of blast mitigation should also bring increased interaction between different agencies at all levels, in what is referred to as a technology transfer in engineering, architectural, and building practices, as well as various procedural aspects (Commission on Engineering and Technical Systems 2000, 31-32). As the civilian community struggles to keep up with the military in terms of blast mitigation design, the quest for knowledge and design guidance will spur the need for the formation of multifunctional groups consisting of members from various federal agencies, the academic community, professional organizations, and the private sector. Soon after, members of the international community will also request to benefit from this national and international technology transfer. This meeting of the minds will spawn documentation, design guidance, and lessons learned to assist the planner, designer, and engineer in the construction of future facilities, with blast mitigation and other requirements in consideration. In addition, there will be more consolidation of codes and standards, perhaps even at the international level. In short, the future should bring more consolidation and communication between the various agencies involved with blast mitigation design and execution at the national and international level, between the military and civilian communities.

Proof of Effect: How Can Effectiveness be Measured?

One of the remaining questions after looking at the entire armed services blast mitigation program is “was it worth it?” or more accurately “did the program achieve the desired effect?” For blast mitigation, that is a difficult question to answer. The only way to be 100 percent certain of the effect is to subject the building in question to the appropriate blast effects and then measure the results. Obviously, this is not feasible nor does it meet the common sense test. However, often times that question must be answered as part of an internal or external review, or in justification of present or future budgets. So, short of blowing up the building, how can the effectiveness of the blast mitigation materials and methodologies be determined?

The first and most common method of determining effectiveness is to perform a paper analysis of the facility structure showing all appropriate calculations. However, this is a very dry method that shows the math is correct and the design criteria is utilized, but is not qualitative to the nonengineer. Showing a congressman a voluminous structural calculation analysis as proof of effectiveness will not further efforts much. Also, it is tedious, time-consuming, and subject to human error that may be very difficult to detect.

Utilizing the results of tests conducted on blast mitigation materials and methodologies can provide some measure of effectiveness, more so than just the paper analysis of the system being tested. Individual materials and facility subsystems can be tested during formalized testing, and the results combined to form a mostly complete picture of how the facility will react to blast effects. While this is more robust than paper analysis on its own, testing the individual materials and subsystems does not take into account the interaction between the individual parts and how that changes the impact of the blast effects.

Virtual Testing: Computer Simulation Software

A useful tool that is used to help identify potential blast vulnerabilities in facilities and to validate possible construction and renovation solutions is the computer, specifically one running blast mitigation software. Most government organizations including the armed services use one or more of these applications as part of their blast mitigation program. The software allows the user to build a real facility within the confines of the virtual space (corresponding to an actual or planned facility), stock it with personnel in the locations anticipated at the time of an explosion, and subject it to the effects of different explosives to observe the impact of the blast on personnel and the structure itself. The simulation can be run over and over again, subjecting the facility to a multitude of singular or multiple explosions, with different population loads, and with different improvements to the facility in a relatively short amount of time. The simulation allows the researcher to collect an immense amount of data about the facility in a short amount of time, without having to subject the facility to any of the dangerous effects of a blast event. There are a group of different programs available to the user; two of the government sponsored packages are the Blast Effects Estimation Model (BEEM) from USACE and Blast/FX, made by Northrop-Grumman for the FAA.

The BEEM program was produced by the USACE PDC in Omaha, Nebraska. The program was developed from two existing programs: the Corps' own Geotechnical and Structures Laboratory AT Planner and the Navy's Force Protection Tool (Sattler 2004).

The program was designed to help both the civilian designer and the warfighter, by being flexible enough to handle permanent, semi permanent, and temporary facilities. The user uses graphical layouts to construct the facility or facilities in question using the interface to select actual materials and design criteria. Personnel zones are also established, marking the area where personnel would be located along with the number expected in the area. Finally, the threat is defined by type of weapon, fragmentation details, size, and location. Once the simulation is run, the program displays results that reveal how the blast affected the facilities and the personnel in and around the facility. This information can then be used to make improvements to the existing facility, as well as make operational adjustments in the surrounding area to control the threat.

The Blast/FX program was created by Northrop-Grumman Mission systems for the FAA Aviation Security Research Division. However, it has been widely distributed throughout the US government as well as civil aviation security agencies and other authorized recipients (Northrop Grumman Mission Systems, 2003). The Blast/FX program is very similar to the BEEM program, allowing the user to build a 3-D building complete with population levels and subject it to different blast effects to determine the resultant damage on the facility and the population (see Figure 7). Like the BEEM program, it is user friendly, but requires an engineering background to be able to accurately enter the parameters for the facility being tested.

Figure 7. Damage and Casualty Estimates for a Specified Scenario – Blast/FX
Source: Northrop-Grumman, “Blast/FX Screen Shots,” *Blast/FX Explosive Effects Analysis Software;* available from http://www.blastfx.com/screen shots.html; Internet; accessed on 10 March 2005.

Simulation software comes with both advantages and limitations. The advantages are speed, convenience, affordability and reliability. While actually constructing the facility within the program can be laborious, it is no more so than completing a complete structural review (with all calculations) of a specific facility. Normally the process is a straightforward method of choosing appropriate construction materials and putting them together roughly in the same way that the building is or will be constructed. Once the facility, the surrounding area, the projected population, and the potential threats have been put into the system, the user can run multiple scenarios with different weapons from different locations and heights. These different scenarios can be analyzed together to determine the weak points of the facilities for all the different possible threats. Those weak points can then be updated in the facility model and the tests rerun until the user finds the correct combination of improvements or changes that will render the subject facility most resistant to the various threats. Convenience is also an advantage for many of the same reasons as speed. It is much easier to run multiple scenarios on the computer than it is to conduct multiple tests in the field; additionally, tests in the field can only address one or two aspects at the same time due to limitations and cost. Virtual testing allows the components of the test to be set, such as the facility structures, and then reused over and over again, making it very easy to test different scenarios when only a single aspect has changed. Computer simulation training is very cost effective and affordable, because the cost of the equipment and software is a one time purchase, while the continuing costs are limited to manpower to operate the simulation. Finally, the system is very reliable. Calculations are based on specified tables and formulas that are programmed in to the software. Users provide the raw data that the computer crunches through those algorithms with no errors in calculation. The computer can also screen the data to ensure it is inside boundaries that are appropriate for the application. For example, an eight inch wall is believable, but an 88 inch wall is not feasible and the program would ask the user to verify. Therefore, if the user inputs the keys data correctly, the computer will deliver, in a very short time, a detailed analysis devoid of any math errors.

On the other hand, there are some limitations to using the blast simulation programs as well, which include limitations in the programs, applicability to real world, and ability to handle complex scenarios. There are limitations in each program that may skew the data received for a single or group of scenarios. These limitations could include the types of materials available, the building techniques available, and the types of explosives. Materials differ from company to company and type to type, and these differences cumulatively could cause the simulation to give results that differ largely from reality. Different types of wood have different properties that could affect the results; windows in the program might not match the windows that are actually at the site, and other minor differences. The same applies to methodologies; a possible scenario could have a concrete block wall reinforced with steel cable, and the scenario has no way to replicate that particular installation methodology. This also applies to weapons, where a homemade bomb may be different enough from the scenario settings to not be replicated in the program appropriately. These differences might be compensated for, but the error margin might be off enough to cause a skewed interpretation of the results. Another limitation is the applicability to the real world. The real world has a lot of variables in it, including examples such as weather, flora, differing elevations, atmospheric conditions, random events, and other aspects that are hard to capture in the software program but could have a real effect on a blast event. This can be overcome to some degree by calculating worse case scenarios, but it still represents a limitation. The last limitation is the ability (or inability) to handle complex situations. Some of the simpler programs only have the ability to analyze a single blast event from a single location. However, a credible threat may involve multiple blasts from multiple locations at the same time or in close time proximity to each other. This would be difficult to calculate by any means, but it does represent a limitation that users should be aware of.

Overall, the use of blast effect simulation programs is an extremely useful application for all agencies and private sector companies to use as part of their blast mitigation vulnerability analyses. The armed services' use of BEEM, Blast/FX, and other programs is an important way to test vulnerabilities within their existing facilities, project vulnerabilities in future facilities, and predict the effect of incorporating new technologies and methodologies in renovation and construction programs. These products should not be single deciding factor, but additional information used in conjunction with other sources of information to provide a full and complete picture.

Case Studies on Improved Construction Materials and Methodologies

As mentioned before, the only 100 percent sure way of testing a facility's level of protection against blast effects is to actually apply those effects to the facility in a controlled experiment and observe the response. For obvious reasons, this is not practical. However, the unfortunate occurrences of terrorist bombing attacks on US facilities can be studied post mortem to get the most realistic information next to observing the actual events as they occur. Outstanding after action reports have been compiled by knowledgeable forensic engineers that outline in graphic detail how the facility reacted to the effects of the blast event, and in some cases also make recommendations for future lessons learned on what could have been done differently to reduce the damage to the facility and injuries to the occupants. Two different case studies were examined, with emphasis noted on what materials and methodologies performed solidly, which failed, and what could have been done better. The case studies noted in this analysis are the 1995 Alfred P. Murrah Federal Building bombing and the Pentagon aircraft strike on 11 September 2001.

Alfred P. Murrah Federal Building, Oklahoma City, 19 April 1995

At 9:02 a.m. on 19 April 1995, an explosive device was detonated from the street in front of the Alfred P. Murrah Federal Building in Oklahoma City, killing 168 people and injuring hundreds. The bomb consisted of 2.5 tons of ammonium nitrate and fuel oil (ANFO), purchased for a total cost of approximately $4,400 and the rental cost of a 20 foot Ryder truck (Oklahoma Bombing Investigation Committee 2005). The bomb was delivered in the Ryder truck and parked in a parking space in front of the building, 14 feet from the northern wall (see Figure 8). The resulting blast was roughly equivalent to 4,000 pounds of trinitrotoluene (TNT), and left a crater in the ground 28 feet in diameter and 6.8 feet deep. The facility was constructed in accordance with appropriate building codes, but contained no special built in resistance to a vehicle delivered explosive blast (Corley et al. 1997, 36-37).

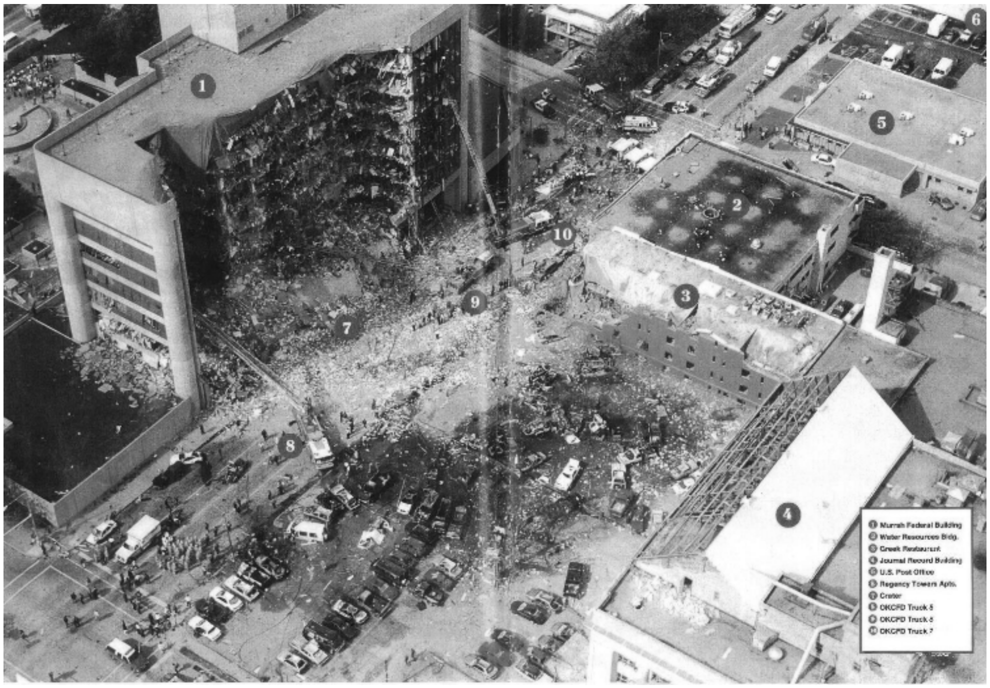

Figure 8. Alfred P. Murrah Federal Building, 19 April 1995
Source: William F. Jasper, "Oklahoma City Bombing: Expert Analysis," *Sovereign Man under Yhwh, in spite of an enslaving world!;* available from http://www.autarchic.tripod.com/files/graham-photo5a_lg.html; Internet; accessed on 8 March 2005.

The fact that the Alfred P. Murrah Federal Building was not constructed to be specifically resistant to the blast effects of a vehicle bomb played a large role in the type and amount of damage done to the facility. The damage encountered was typical of that encountered in similar bomb blasts against facilities that are not strengthened to withstand the blast effects. What makes this case interesting and relevant is that the old building was torn down after the bombing and replaced with a memorial park and a new improved facility across the street, one that was designed to be both attractive and resistant to a threat similar to the one that destroyed the original.

From a structural point of view, the building was sound. The facility was a nine story reinforced concrete frame facility with three rows of columns spaced at 20 feet, with a large transfer girder on the third floor that permitted the elimination of alternate columns on the first and second floor (Corley et al. 1997, 36). The first order blast effects caused the immediate failure of three columns and floor slabs up to the fifth floor. The closest column to the blast was an exterior column supporting the transfer beam. It was completely obliterated by the blast. The two adjacent columns supporting the transfer beam were also damaged by the blast, sheared off between the second and third floor. The exterior façade was constructed of aluminum frames supporting 5 foot by 10 foot glass panels, which offered no blast protection and contributed toward the second and third order damage effects. The floor slabs between the three columns were immediately destroyed from the first floor up to the fifth floor as a result of the upward blast pressure wave (Corley et al. 1997, 41-42). Additional damage occurred on interior columns and additional floor slabs all the way up to and including the roof as a result of second and third order blast effects including progressive collapse. Lessons learned from this incident include the importance of stand-off distances, structural redundancy, and limitations on glass cladding from the street level (Lim 2003, 43). While stand-off distances are difficult in urban settings, the south side of the building was offset enough from the main road to offer a certain amount of protection. However, the north side (which was the site of the blast) was immediately adjacent to the road and offered little or no stand-off distance. The use of large columns and a transfer beam on the third floor reduced the number of columns directly supporting the building, removing redundancy from the structural support system. Glass walls on the first three floors of the facility provided no blast protection to the facility. The use of reinforced walls for the first three floors would have significantly strengthened the section of the facility most at risk from a near ground level blast event (Lim 2003, 43).

After the bombing, what remained of the facility was not usable and was required to be torn down for safety and practical reasons. The site was redesigned to accommodate a memorial site on the previous building footprint, and a new facility was sited across the street. The design of the new facility was awarded to Chicago architect Carol Ross Barney, who spent considerable time researching not only the physical requirements of the facility, but the cultural expectations of the new facility. Her biggest challenge: designing a building that met the Security Level IV safety standards without building a glorified bunker (Becker 2004). While stand-off distances were just as difficult to deal with in the new facility, the new facility has a row of concrete bollards all around the facility, ensuring that no vehicle will get closer than the street to the facility. Along the street elevations, the exterior walls are reinforced concrete, with inset windows that complete the urban appearance. The windows are blast resistant, using laminated glass and reinforced frames strengthened to absorb the flex of the glass subject to a blast pressure wave without releasing it. The entrance to the facility is a large glass courtyard, located on the north side, set back and centered in the middle of the facility to limit vehicular access. The windows themselves are laminated as well, with an extensive steel curtain wall to support the glass even under the stresses of blast pressure waves (Becker 2004). The new facility is as attractive as it is solid and resistant to blast effects, effectively marrying the form with the function (see Figure 9).

Figure 9. New Federal Building, Back Side, Oklahoma City, Oklahoma
Source: Brad Goldberg, "Architecture in a time of fear," *Repeat: An archive of writings on architecture in Chicago and the world,* written by Lynn Becker; available from http://www.lynnbecker.com/repeat/rossbarney/oklacity.htm; Internet; accessed 14 March 2005.

Pentagon Aircraft Strike on 11 September 2001

On 11 September 2001, the Pentagon was struck by a Boeing 757-200 aircraft, shortly after taking off from Washington Dulles Airport. The impact occurred in a section of the Pentagon that had been recently renovated; the aircraft plunged into the building at an angle, punching through the renovated section and into the unrenovated section approximately at ground level (see Figure 10). The impact of the aircraft and the resulting fire from the unspent fuel eventually caused a collapse in the area immediately above the impact site in the outer ring. While this was an opportune chance to examine a recently upgraded blast mitigation application subjected to an actual event rather than a controlled event, there were some mitigating factors. The biggest mitigating factor was the weapon of choice, the use of a commercial passenger airliner loaded with aviation fuel as an explosive agent. The use of a passenger aircraft introduced a different set of forces on a subject target: the forces of impact. Maximum take off weight for a Boeing 757-200 is 255,000 pounds; propelling this aircraft at 460 knots and impacting a target introduced a huge penetration force not found in any of the identified threats mentioned earlier in the analysis (Mlakar et al. 2003, 12). Therefore, the most relevant data in the Pentagon case study to examine (within the confines of this analysis) is contained within those areas immediately adjacent to the aircraft strike area; in other words, those areas less affected by the aircraft impact and primarily subjected to the blast effects of the aviation fuel explosion.

As part of the renovation project, the exterior windows of the Pentagon were strengthened against blast effects with reinforced frames and blast resistant glass. Pictures of the Pentagon immediately after the strike and prior to the collapse showed that the reinforced windows survived the impact and the following explosion rather well, even windows that were within 10 feet of the impact site (Mlakar et al. 2003, 16). Nonrenovated windows in the same area did not nearly as well; most of the nonrenovated windows in the area and up to 200 feet away from the strike site were broken as a result of the impact and following explosion. In addition, the exterior walls of the Pentagon without windows responded relatively well to the impact and resulting fire, considering the fact that the engineering design was not completed with aircraft impact in mind.

The newly renovated section of the Pentagon had also incorporated additional structural improvements, intended to reduce the risk of progressive collapse in the event of abnormally large loads. This improved structural design included providing redundancy in various structural aspects such as load paths, bottom beam reinforcement, and the two way beam and girder system; energy absorbing capacity in the columns; and the ability of the exterior walls to act as transfer girders (Mlakar et al. 2003, 58). While a section of the building did collapse, the cause was primarily due to the extreme temperatures generated by the infusion of aviation fuel directly into the facility through the impact area. Heat damage to the protective surfaces and impact damages to the inner components caused the collapse; however, the damage due to the blast itself was relatively small. Minus the initial impact and the high temperatures resulting from the burning fuel, the improved structural portion of the Pentagon performed quite effectively.

Figure 10. Pentagon on 11 September 2001 after aircraft strike
Source: Donley, Daryl, "Explosion," *Witness and Response: September 11 Acquisitions at the Library of Congress;* available at http://www.loc.gov/exhibits/911/images/01749r.jpg; Internet; accessed 8 March 2005.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

As the analysis was presented in a framework that analyzed pieces of the overall question in the form of secondary questions to make it more palatable and easier to digest, it seems fitting that the conclusions and recommendations would be presented in the same manner. Each secondary question was summed up and at the end the entire framework of the analysis was presented with regard to the fore mentioned pieces. Afterwards, recommendations were presented that would provide a stepping stone to further aspects of study related to this theme, either as a continuation to what was presented or a parallel effort that would expand the scope of the presented information.

Building the Framework: How Should the Terms be Defined?

Definition of the terms normally does not result in any conclusive determinations, and is more of a shaping action than a main effort. The terms discussed in the analysis helped to provided limitations and focus to a specific aspect of the problem to be resolved, to allow a more in-depth analysis than could be undertaken in this relatively short space. However, it is significant in that the focus is upon the permanent garrison facilities not the deployed personnel or forward operation points. By specifying permanent garrison facilities the definition of the enemy to be defended against is decidedly non-military, or asymmetric in nature at the very least. Probably this is the most conclusive argument produced in this section, which leads to the realization that protecting these permanent facilities against one threat does not make them impervious to the other threats. The case study on the Pentagon aircraft strike on 11 September 2001 drives that idea home. Although the enemy was the same, the mode of attack was different; the facility was not (and probably could not have been) designed to withstand the impact of a loaded airliner traveling at over 500 mph. The strike did not render the blast mitigation efforts in the facility ineffective, but did exceed the damages expected for the envisioned vehicle bomb effect.

Bottom line conclusions from this part of the analysis: Blast mitigation is all about achieving a balance between protection, aesthetics, and cost; blast mitigation is but one part of a total force protection and antiterrorism package; and effective use of blast mitigation materials and methodologies is threat dependent; different or adapted threats do not render blast mitigation ineffective but may decrease effectiveness.

The Current List of Innovations in Materials and Methodologies

Similar to a host of other programs in the US government, blast mitigation is driven by the economic principal of supply and demand. The development process is driven by the amount of financing that is put against it, which is a direct result of the level of interest. With regards to blast mitigation since 1993, the federal government has focused increased interest (and a correspondingly large budget) on improving government facilities against potential vehicle explosive devices. This interest has stimulated private sector companies and organizations to concentrate their efforts as well on supporting this program. All this associated interest has been a catalyst in the development of new and improved materials and methodologies in blast mitigation.

As far as materials are concerned, the vast array of potential products to reduce the impact of blast effects can be boiled down into a small group of classes: Doors, windows, curtains, wall materials, applied coatings, and exterior structures. All categories contain elements applicable to both new construction and renovation applications. Construction methodologies, on the other hand, can be divided for the most part into three classes: Design considerations, blast redirection, and energy absorption, of which design considerations primarily apply to new construction, while the other classes can apply to both construction and renovation. All classes, for both materials and methodologies, contain elements that are relevant for use by the armed services and can be considered to be realistically executable, both in financial and technical terms.

When surveying the amount of data pertaining to blast mitigation in terms of test results, analyses, products information, and other data sources, it is abundantly clear that the US has taken the lead in the development of blast mitigation products and techniques. No doubt, there are a lot of countries in the world with some experience in blast mitigation development, but only the US has the industrial engine and the government resources required to keep that engine turning and the drive to capture those requirements into guidance and documentation. That being said, there are also plenty of examples of interactions between the nations targeted for these kinds of attacks and cooperation at the corporate, working group, and governmental levels.

Bottom line conclusions from this portion of the analysis include: Federal interest in blast mitigation since 1993 has encouraged the private sector to focus on developing more and better materials and methodologies for mitigating the effects of potential blast events; these materials and methodologies represent real and plausible approaches toward delimiting blast effects; and the US has taken the lead in the development of blast mitigation materials and methodologies, although other international governments and organizations continue to contribute both individually and collectively with the US.

Testing, Assessing, and Validating Blast Mitigation Materials and Methodologies

The formation of the TSWG was a significant achievement for all federal organizations involved with force protection and antiterrorism. It formalized the free and open exchange of information between all the members, resulting in a huge pool of lessons learned, test results, and other resources that helped shaped the individual organizations' programs. The armed services already had a robust testing and assessment program in place, with each of the armed services having their own testing facilities and analysis teams to interpret those results; the TSWG allowed all to take advantage of each others' information. A notable fact about the TSWG is that it is international in nature, including Britain, Canada, and Israel as members in the free and open share of information. Incorporation of lessons learned from international partners who have been fighting the asymmetric enemy for many years can be particularly beneficial to the individual armed services' programs.

Increasingly, there should be a larger share of the testing and analysis outsourced to the commercial sector in accordance with the US government's current policy of moving all non-warfighting tasks to the civilian segment of the armed services or to the private sector. This is not considered a liability, but it does open some different areas of concern. The private sector has members that are fully capable of providing the kind of testing and analysis necessary to support the blast mitigation programs of the armed services. However, it is important that the armed services keep a strong hand in the validation of the feasibility of materials and methodologies, even if the work is being accomplished by others under some sort of a performance contract.

Bottom line conclusions from this portion of the analysis are: Knowledge and information sharing with other federal organizations and international partners is a multiplier that should be fully utilized to improve the armed services' programs; and increased outsourcing of testing and assessment is anticipated in the future and the armed services must continue to pursue results aggressively regardless of who is accomplishing the field work.

Changes to Construction and Renovation Standards

The DOD solidified the foundation for blast mitigation and force protection standards by producing the *Unified Facilities Criteria: DOD Minimum Antiterrorism Standards for Buildings*. This document provides a creditable, comprehensive baseline for all the armed services to build their individual programs on. The document is flexible and delineates the steps and criteria necessary to protect permanent facilities from the current perceived threat. A vision is produced, showing five overarching guiding principles, which is supported by twenty-three standards and sixteen recommendations.

Using the fore mentioned foundation as a starting point, the individual services have developed further, more detailed guidance and standards that provide the planner and designer with specific information that can be used in the design of new and renovated facilities. For the most part, the services subscribe to the same basic set of protection standards, and then customize them on a facility by facility basis based on threat of enemy action, risk of possible attack, personnel in the facility and surrounding area, site layout in the general vicinity of the target facility, and other site specific details.

Other federal organizations have undertaken parallel efforts in the development of improved blast mitigation facility criteria. Most noticeably of the group are the DOS and the DOJ, primarily due to their experiences pre-1993 (embassies) and post-1993 (embassies and federal buildings) with terrorist attacks via vehicle and other portable explosive devices. These documents also address the organization specific threat, risk and function, but maintain that level of openness to allow for site specific flexibility.

The bottom line conclusions from this section of the analysis are: The DOD has established an excellent foundation for blast mitigation criteria for the armed services in the *Unified Facilities Criteria: DOD Minimum Antiterrorism Standards for Buildings*; each branch of the armed services has additional design guidance and other service specific guidelines to build upon the DOD minimum standards for blast mitigation; and other federal organizations have developed similar documents for their organizations, which are shared with the armed services and other partners through the TSWG.

The Future of Blast Mitigation Innovations

Continued evolution and spontaneous innovation of blast mitigation materials and methodologies is an adequate summation of the future of the blast mitigation program. Existing materials will continue to evolve; for example, concrete will get stronger, easier to use, lighter, cheaper, and increase its energy absorbent characteristics. These improvements will increase the ability of the materials to resist the blast characteristics inherent in a subject blast event. There will also be innovative jumps in materials, such as the discovery of new materials, new uses for existing materials, and other such revolutionary jumps. Consider the “transparent aluminum” example given previously; while fictional, there are no doubt materials that will be developed that will provide the same type of revolutionary jumps. Methodologies will also evolve and make innovative leaps ahead in the future. Production and application methodologies will be streamlined and enhanced to provide and utilize the required product faster, more economically, and more effectively. Consider the spider web example given earlier; revolutionary jumps in production and application methodologies could result in an economical, efficient way of using a material that was previously not viable.

Another aspect of blast mitigation improvements in the future is the increased interaction between different agencies at all levels within the organizations. This is part a communication improvement and part a technological improvement. Already there is interaction between agencies for issues pertaining to force protection and antiterrorism (referring to the TSWG), which also includes some international players. In the future, increased interaction between all agencies at all levels can be expected, including state and local government offices. Increased interaction with the private sector will also spur improvements and interagency communications. Finally, expect more international involvement as well, as other nations find themselves subject to similar threats and situations as experienced by other members of this community.

The bottom line conclusions from this section of the analysis are: Blast mitigation materials and methodologies will continue to make evolutionary steps and revolutionary leaps forward in the future; changing threats in the future will most likely drive the improvement and innovation process of blast mitigation materials and methodologies; and the future will bring increased interaction between interagency, international, private sector, state, and local government in a technological transfer intended to bring program continuity across the board to all members of the community.

Proof of Effect: How Can Effectiveness be Measured?

Measuring effectiveness of blast mitigation in a facility is truly a two edged sword; the only sure way of determining it is to subject the facility to the anticipated blast event and observe the results. However, there are other methods that are less intrusive to the facility, and can provide a level of surety that the innovations incorporated in a facility's design and construction will provide the protection specified. The first and second methods are lumped together; they include the structural analysis that is part of the design of a facility and the individual testing that goes into each material and methodology used in the blast mitigation effort. The structural analysis can provide the proof that the facility can withstand the forces generated by the blast event, and the individual test results can provide assurance that the individual pieces will react as expected during the blast event. Both of these are effective and necessary, but lack the ability of iterative recombination to determine the best and most effective design.

There are a number of computer simulation programs available, including BEEM and Blast/FX, which give the designer the ability to use iterative recombination to change one aspect, look at the results, change another aspect, and so on. This gives the designer the ability to determine the most effective blast mitigation structure without having to rerun the structural analysis repeatedly. While there are advantages and disadvantages to use of this software, it appears to have great value as part of a total blast mitigation analysis of a new or existing facility. One additional particular advantage to the system is the ability to produce results visually, rather than a stack of numbers and tables. This makes the program very useful for explaining and demonstrating effectiveness to an audience that may not have the experience of the structural engineer.

The case studies provide some interesting reading, and help to validate the improvements made in the pursuit of blast mitigation. The most probable use for case studies such as these is validating the threat and using the information to refine the blast mitigation to meet a more realistic threat. In the case of the Pentagon, the results did somewhat bear out that the improvements made to the facility to improve its ability to resist blast effects. Unfortunately, this had to be somewhat inferred since the attack was not a vehicle bomb outside the Pentagon, but a Boeing 757 striking and penetrating deeply into the facility. Rather than proving to be an effective test bed for blast mitigation innovations, the case studies better defined the threat, which in turn could generate more realistic testing criteria for blast mitigation innovations in materials and methodologies.

The bottom line conclusions from this section are: The structural analysis must be done as part of the design process, but other methods exist that can provide proof of effectiveness in a more graphic fashion and in a manner that is more qualitative and concrete; material and methodology testing results can definitely enhance the structural analysis, but they do not incorporate the facility as a system in the test results; the use of blast effect simulation programs are extremely useful in determining effectiveness of blast mitigation precautions and identifying potential vulnerabilities; and the examination of case studies in terrorist bombings, while useful in helping to better refine the threat criteria for blast mitigation design and testing, provides limited usefulness in determining effectiveness of blast mitigation innovations (this however is time situational; an attack in the future, depending on the circumstances, could provide some very effective information).

The Crux of the Matter: Has Effective Use Been Made?

Throughout this analysis, the actual defining characteristics of “effectiveness” have been nebulous and difficult to nail down to a specific checklist of criteria. At this point in the analysis, several characteristics have become apparent; perhaps these characteristics, when summed up, provide a rough boundary around the area of effectiveness. The effective use of innovations in materials and methodologies for blast mitigation by the armed services can thus be summed up with the following characteristics.

Are the armed services aware of innovations in materials and methodologies in blast mitigation? Yes. The armed services routinely test materials in their own laboratories as well as outsource out testing to qualified private sector facilities. Also, with the increased focus on antiterrorism at home (and abroad), the capitalistic nature of US industry has driven an active effort to develop, test, and market blast mitigation materials and methodologies to federal organizations and private sector customers. Military and military related trade journals routinely report on the development of new and improved materials and methodologies, giving all customers unfettered access to the latest product information and test results.

Have the armed services made efforts to craft and adapt design guidance and other guidelines to permit and encourage the use of improved blast mitigation materials and methodologies? Yes. In the years following the 1993 WTC bombing, all federal agencies have made great strides in harnessing developing insight on vulnerabilities in federal facilities, and crafting guidance that would mitigate those vulnerabilities. On the whole, the US has taken the lead on the international level in developing and incorporating blast mitigation innovations. On the DOD side of the house, the DOD developed a minimum standards list for buildings, addressing all aspects of antiterrorism including blast mitigation. These standards provide the bare minimum of what is required to protect people inside of facilities, and set the framework for the armed services to impose stricter and more detailed service specific guidance as per their requirements. The services have responded accordingly, by developing guidance that meets the specific needs of their own facilities and assets. The armed forces also remain in touch with other federal agencies and select international partners through the TSWG, and are therefore privy to innovations and policy changes throughout the federal organizations.

Do the armed services have a feedback system with the blast mitigation process which gauges performance of the process and specific program details and allows for changes to improve? Yes. The armed services routinely test materials and methodologies to assure that they perform within the specified parameters. These materials and methodologies are incorporated into the design of facilities. Part of the design process includes a structural analysis, which determines if the facility can withstand the forces generated as a result of a blast event. This analysis is assisted through the use of developed software applications that allow the designer to subject the facility materials and design to multiple blast event scenarios, to determine the extent of damage and identify critical vulnerabilities to correct before going final on the design. In the event of an actual blast event, a post mortem engineering and structural analysis is performed to identify the failed components in the facility, to reconstruct the chain of events leading to any facility failures, and to identify any lessons learned as a result of the blast event.

From a policy and documentation point of view, the DOD's involvement with the TSWG allows the DOD to see how other organizations are pursuing blast mitigation.

Are the armed forces preparing adequately for the future in terms of blast mitigation? Yes and no. The armed forces have the capability to recognize and integrate future innovations in blast mitigation materials and methodologies, as delineated in one of the previous characteristics. The armed services already have the capability as well to allow for technological transfer of blast mitigation information between other federal organizations, international representatives, and any future partners such as local and state governments. The armed forces are making effective use of innovations in materials and methodologies for blast mitigation in new and renovated facilities based on the present threat, not in anticipation of a future threat. As the blast mitigation program (as well as the force protection and other aspects of the antiterrorism process) improves and lowers the threat to facilities targeted by terrorists, the terrorists will improve their attacks and utilize capabilities designed to overpower or circumvent our blast mitigation program. The Pentagon aircraft strike on 11 September 2001 proved that; the facility was no longer vulnerable to a vehicle bomb parked outside the facility, so the threat was adapted to something that would overcome the defenses. For the armed services blast mitigation program to be truly effective, there needs to be some sort of proactive insight built into the process, one that predicts future threat capabilities and designs measures to guard against not only the current threat, but the current and immediate future threat.

Recommendations

The introduction of delimiters into the scope and course of the analysis open the door for future and continued studies in blast mitigation. Primarily, consider the definition of the threat. This analysis is based on a particular threat, in essence a car bomb, RPG or other small portable explosive device. An important aspect to study and consider is the future threat, or what will the threat to these facilities be in the future. The Pentagon aircraft strike on 11 September 2001 was a wakeup call for blast mitigation planners; the blast mitigation threat was previously based on a vehicle bomb such as the one at Khobar Towers, not a fully fueled airliner crashing into the building at destructive speeds. What can be expected next? Bombs with exponentially increased explosive potential? Portable nuclear devices small enough to be delivered in a backpack? Weapons that use high frequency, high amplitude sound waves to destroy a building? Another approach to quantifying the future threat would be to predict the impact of a changed threat upon our existing facilities, especially the ones considered to be adequately protected.

Interactions between other countries and the US on blast mitigation materials, methodologies, and techniques offer an encouraging opportunity for further research and analysis. A focused look at efforts undertaken in Tel Aviv, Belfast, or Johannesburg would make a fascinating parallel study to the theme of this analysis. Another similar angle would be to try and better quantify the amount of knowledge and experience from these other countries brought to joint and combined interactions between the US and other countries. These interactions could be examined from the doctrinal, governmental, and private sector level of interaction to provide a complete and rounded picture of international cooperation in blast mitigation efforts.

Additional research into the capabilities of the private sector to support the armed services blast mitigation program may provide some interesting insights as well as useful information for future study. Since it is entirely likely that an increased percentage of testing and analysis could go to the private sector under contracts, it would be interesting to see who the top ten companies are who do this kind of work are, what their background and experience levels are, and what work have they done previously (independently or under contract from another public or private organization) that could be immediately incorporated. In addition, a feasibility study could be accomplished to determine just how necessary it is for the armed services to operate their own blast mitigation materials and methodologies testing facilities.

Incorporation of blast mitigation details and requirements into construction standards and guides has been a recent development (since 1993), and has happened on parallel tracks for different services, federal agencies, and multi-organizational, multi-national organization groups. An interesting and useful research venture would be to put together and construct a timeline laying out what steps were taken, what documents were published and adopted, what order they occurred in, and what was the stimulus for each particular evolution. Similarly, a compendium of all these changes, standards, and requirements by functional or technical area would be another useful document to have and a worthy undertaking as a point of reference for blast mitigation professionals.

Pertaining to future materials and methodologies, it would be interesting to conduct a future study group and brainstorm a possible future scenario given the current threat and technology level which predicts changes in the threat and resultant changes to the level of force protection and blast mitigation that military facilities will require. Once this future scenario is developed, it could be used to compare to existing standards and risk analyses to determine how effective our facilities and procedures of today would fare in the future scenario. While it could end up being an interesting case of technical science fiction, it could just as easily provide some sort of insight that could help steer the program of today into the program of tomorrow.

Another interesting study to pursue would be to test some of the various software modeling programs against each other for accuracy, as well as against some actual events to determine just how accurately the programs predict the level and extent of damage. There are numerous blast effect modeling programs, and consumer style analyses of each program's strengths, weaknesses, and capabilities would be of interest to anyone using the software or considering using the software in the future. Part of the test could include building a scenario based on an actual event, such as the Khobar Towers or the Alfred P. Murrah Federal Building bombing, and then running it through each program to determine results. A comparison of the results from each program with the actual event would show just how accurate (or how inaccurate) the modeling software would be. An analysis of this nature would be of interest to planners, designers, and engineers of all types, especially structural engineers, force protection planners, and antiterrorism specialists.

GLOSSARY

Blast Mitigation. An action that reduces or eliminates risk to people and property from explosive devices and their primary and secondary effects.

Invention. The creation of a new idea or concept

Innovation. The result of turning an invention into commercial success or widespread use, including all the steps from the inventor's idea to bringing the new item to market

Materials. Physical products used for blast mitigation

Methodologies. The actions, procedures, and techniques used to incorporate materials in a blast mitigation program

New Facility. A facility constructed from the ground-up, culminating with a complete and usable building and associated grounds; includes all work and materials necessary to demolish existing structures, prepare the site, construct the facility, and provide landscaping, utilities, and access

Renovated Facility. A previously existing facility that has been retrofitted within the confines of the existing structure without increasing the existing living and working space; includes all work and materials necessary to improve the existing facility and provide a complete and usable facility

APPENDIX A

SUMMARY OF DESIGN STRATEGIES (UFC 4-010-01)

Standard 1: Minimum Standoff Distance. Applies to new and existing buildings, when triggered.

Standard 2. Building Separation. New buildings must be separated to minimize collateral damage.

Standard 3. Unobstructed Space. Ensure that obstructions within 10 meters (33 feet) of inhabited buildings do not allow for concealment of explosive devices 150 millimeters (6 inches) or greater in height.

Standard 4. Drive-Up/Drop-Off Areas. Do not allow drive-through lanes or drive-up/drop-off to be located under any inhabited portion of a building.

Standard 5. Access Roads. Ensure that access control measures are implemented.

Standard 6. Parking Beneath Buildings or on Rooftops. No parking underneath or on roof tops.

Standard 7. Progressive Collapse Avoidance. For all new and existing inhabited buildings of three stories or more, design the superstructure to sustain local damage with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage.

Standard 8. Structural Isolation. Additions to existing buildings must be structurally independent from the adjacent existing building

Standard 9. Building Overhangs. Avoid building overhangs with inhabited spaces above them where people could gain access to the area underneath the overhang.

Standard 10. Exterior Masonry Walls. Unreinforced masonry walls are prohibited.

Standard 11. Windows and Glazed Doors. Use a minimum of 6-millimeters (1/4-in) nominal laminated glass for all exterior windows and glazed doors. Frames and mullions must be aluminum or steel.

Standard 12. Building Entrance Layout. The main entrance to a building must not face an installation perimeter or other uncontrolled vantage point.

Standard 13. Exterior Doors. Ensure that exterior doors into inhabited areas open outward.

Standard 14. Mailrooms. Locate rooms where mail is delivered or handled, to limit collateral damage.

Standard 15. Roof Access. Control access to roofs to minimize the possibility of placing explosives or chemical, biological, or radiological agents where they would threaten occupants or infrastructure.

Standard 16. Overhead Mounted Architectural Features. Ensure that overhead mounted features weighing 14 kilograms (31 pounds) or more are securely mounted.

Standard 17. Air Intakes. Locate air intakes at least 3 meters (10 feet) above the ground.

Standard 18. Mailroom Ventilation. Provide separate, dedicated air ventilation systems for mailrooms.

Standard 19. Emergency Air Distribution Shutoff. Provide an emergency shutoff switch in the HVAC control system.

Standard 20. Utility Distribution and Installation. Route critical or fragile utilities so they are not on exterior walls or on walls shared with mailrooms.

Standard 21. Equipment Bracing. Mount overhead utilities and other fixtures weighing 14 kilograms (31 pounds) or more to minimize the likelihood that they will fall and injure building occupants.

Standard 22. Under-Building Access. Ensure that access to crawl spaces, utility tunnels, and other means of under-building access is controlled.

Standard 23. Mass Notification. All inhabited buildings must have a timely means to notify occupants of threats and instruct them what to do in response to those threats.

Source: Bradshaw 2003, 13

APPENDIX B

RECOMMENDED ADDITIONAL MEASURES (UFC 4-010-01)

Recommendation 1. Vehicle Access Points. The first line of defense in limiting opportunities for aggressors to get vehicles close to DOD buildings is at vehicle access points at the controlled perimeter, in parking areas, and at drive-up/drop-offs points. Keep the number of access points to the minimum necessary for operational or life safety purposes. This will limit the number of points at which access may have to be controlled with barriers and/or personnel in increased threat environments or if the threat increases in the future.

Recommendation 2. High-Speed Vehicle Approaches. The energy of a moving vehicle increases with the square of its velocity; therefore, minimizing a vehicle's speed allows vehicle barriers to be lighter and less expensive should vehicle barriers ever become necessary. To facilitate reductions in vehicle speeds in the future, ensure there are no unobstructed vehicle approaches perpendicular to inhabited buildings at the required parking and roadway standoff distances.

Recommendation 3. Vantage Points. Vantage points are natural or man-made positions from which potential aggressors can observe and target people or other assets in and around a building. Identify vantage points outside the control of personnel in the targeted building and either eliminate them or provide means to avoid exposure to them. Means to avoid exposure may include actions such as reorienting the building or shielding people or assets in and around the building using such measures as reflective glazing, walls, privacy fencing, or vegetation.

Recommendation 4. Drive-Up/Drop Off. Locate these points away from large glazed areas of the building to minimize the potential for hazardous flying glass fragments in the event of an explosion. For example, locate the lane at an outside corner of the building or otherwise away from the main entrance. Coordinate the drive-up/drop-off point with the building geometry to minimize the possibility that explosive blast forces could be increased due to being trapped or otherwise concentrated. For further discussion of this issue, refer to the DOD Security Engineering Manual.

Recommendation 5. Building Location. Activities with large visitor populations provide opportunities for potential aggressors to get near buildings with minimal controls, and therefore, limit opportunities for early detection. Maximize separation distance between inhabited buildings and areas with large visitor populations.

Recommendation 6. Railroad Location. Avoid sites for inhabited buildings that are close to railroads. Where railroads are in the vicinity of existing buildings, provide standoff distances between the railroad and any inhabited buildings based on the standoff distances and explosive weight associated with controlled perimeters in

Table B-1. Where those standoff distances are not available, and since moving existing railroads may be difficult and prohibitively expensive, ensure that there are procedures in place to prohibit trains from stopping in the vicinity of inhabited structures.

Recommendation 7. Access Control for Family Housing. For new family housing areas, provide space for controlling access at the perimeter of the housing area so that a controlled perimeter can be established there if the need arises in the future.

Recommendation 8. Standoff for Family Housing. For new family housing construction, maintain a minimum standoff distance of 25 meters (82 feet) from installation perimeters and roads, streets, or highways external to housing areas.

Recommendation 9. Minimize Secondary Debris. To reduce the hazard of flying debris in the event of an explosion, eliminate unrevetted barriers and site furnishings in the vicinity of inhabited structures that are accessible to vehicle traffic. Revet exposed barriers and site furnishings near inhabited buildings with a minimum of 1 meter (3 feet) of soil or equivalent alternative techniques to prevent fragmentation hazards in the event of an explosion.

Recommendation 10. Structural Redundancy. Unexpected terrorist acts can result in local collapse of building structural components. To limit the extent of collapse of adjacent components, utilize highly redundant structural systems such as moment resisting frames, detail connections to provide continuity across joints equal to the full structural capacity of connected members, and detail members to accommodate large displacements without complete loss of strength. This recommendation is consistent with paragraph B-2.1 (Standard 7) for preventing progressive collapse, but recommends selection of certain structural systems and greater attention to structural details.

Recommendation 11. Internal Circulation. Design circulation within buildings to provide visual detection and monitoring of unauthorized personnel approaching controlled areas or occupied spaces.

Recommendation 12. Visitor Control. Controlling visitor access maximizes the possibility of detecting potential threatening activities. Keep locations in buildings where visitor access is controlled away from sensitive or critical areas, areas where high-risk or mission-critical personnel are located, or other areas with large population densities of DOD personnel.

Recommendation 13. Asset Location. To minimize exposure to direct blast effects and potential impacts from hazardous glass fragments and other potential debris, locate critical assets and mission-critical or high-risk personnel away from the building exterior.

Recommendation 14. Room Layout. In rooms adjacent to the exterior of the building, position personnel and critical equipment to minimize exposure to direct blast effects and potential impacts from hazardous glass fragments and other potential debris.

Recommendation 15. External Hallways. Since doors can become hazardous debris during explosive blast events, doors designed to resist blast effects are expensive, and external hallways have large numbers of doors leading into inhabited areas, avoid exterior hallway configurations for inhabited structures.

Recommendation 16. Windows. To minimize the potential for glazing hazards, minimize the size and number of windows for new construction.

Source: US Department of Defense 2002, C1-C3

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