Chapter 3
UPDATE ON SAFETY OF THREATENED BUILDINGS (WTC R&D) PROGRAM

3.1 OBJECTIVES OF SAFETY OF THREATENED BUILDINGS (WTC R&D) PROGRAM

This program is designed to (1) facilitate the implementation of recommendations resulting from the World Trade Center (WTC) investigation, and (2) provide the technical basis for cost-effective improvements to national building and fire codes, standards, and practices. Under the program National Institute of Standards and Technology (NIST) will develop guidance and tools to assess and reduce building vulnerabilities and will support private sector organizations that develop building and fire codes and standards in the United States. Implementation of the results will better protect building occupants and property in the future, will enhance the safety of fire and emergency responders, and will increase confidence in the safety of commercial and public buildings.

Four general areas of research are targeted to support near- and long-term improvements to reduce the vulnerability of the structure, building occupants, and first responders to potential threats:

- Increased Structural Integrity
- Enhanced Fire Resistance
- Improved Emergency Egress and Access
- Building and Emergency Equipment Standards and Guidelines

3.2 BACKGROUND AND DESIRED OUTCOMES OF SAFETY OF THREATENED BUILDINGS (WTC R&D) PROGRAM

Building and fire codes in the United States exist, among other reasons, to ensure the safety of occupants in the event of anticipated excessive loads due to wind, earthquake, and snow, and the potential for severe fires. The tragic collapse of the WTC buildings in 2001 (along with the terrorist attacks on the Pentagon, Hart Senate Office Building, and the Murrah Federal Building) has focused the general public, governments at all levels, and the construction and building products industries on the need to understand the possible impacts of terrorist acts on building operations, structural integrity, and emergency response procedures, and on the need to develop economically justifiable strategies to mitigate the potential loss of life from possible future threats.

The standard test methods and building practices upon which current building and fire codes are based rank the performance of one material, component, or system against alternative designs, with the expectation that some minimum rating translates into a sufficient level of safety of the material, component, or system when installed in a building. Safety factors are used to account for our ignorance abut the magnitude of actual loads, and of the uncertainty in response of the complex building frame to these loads.

The prediction of failure modes in a closely-coupled building system is beyond our current capability, and standard test methods provide little information on the expected performance of the building should the mechanical or thermal load exceed a prescribed value.

In addition, building designers, operators, occupants, and first responders are faced with chemical and biological threats unforeseen as little as two years ago. How should heating, ventilation, and air-conditioning (HVAC) systems be designed and operated to contain a poisonous aerosol or gas? How has the behavior of occupants changed since September 11, 2001, in responding to an emergency? Should the same emergency egress and fire service access techniques and strategies be used in the case of a biological threat as for a fire? Can new technologies be developed, or design practices adapted, to increase the safety of the building occupants without undue economic burden on the owners/operators?

Additional research and development is being conducted in this program to answer questions like these, to provide guidance and tools to assess and reduce future vulnerabilities, and to better prepare facility owners, contractors, designers, and emergency personnel to respond to future disasters, naturally or intentionally initiated.

Increasing Structural Integrity—Structural integrity will be increased through the development and implementation of performance criteria for codes and standards, tools and practical guidance for prevention of progressive structural collapse. System design concepts, retarded collapse mechanisms, built in redundancy, and hardening structures though retrofit are being considered. Performance criteria for fire safety design and retrofit of structures is being developed through examination of five key factors: the suitability of standard fire resistance test methods; the role of structural connections, diaphragms, and redundancy in enabling load transfer and maintaining overall structural integrity; the effectiveness of alternative retrofit, design and fire protection strategies to enhance structural fire endurance; the fire behavior of structures built with innovative materials; and models to predict the fire hazard to structures from internal and external fires. Guidance on methods to enhance fire resistance of steel and concrete structures based upon our current state of knowledge is being developed as well.

Enhancing Fire Resistance—Fire resistant steels exist and are in use elsewhere in the world. More efficient and accurate tests for performance of steels under building fire conditions are needed and are being developed to help industry incorporate fire resistant steels into U.S. construction practice. Fundamental mechanical and thermal properties of fire protective materials are being measured. This requires the development of new test methods and instrumentation, and a data base that spans the full range of expected temperatures and mechanical loads. These data will supplement, or may even supplant the need for, the ASTM E 119 test in certain situations, and in any case are essential to the implementation of meaningful performance codes and design criteria.

Facilities do not yet exist that are suitable for demonstrating in a quantitative manner the improved performance of new materials, systems, and processes in their end-use within a building under actual fire conditions. Hence, simulations are required to bridge the fundamental data and the results of bench- and pilot-scale tests to the environment in which they would be exposed during severe fire conditions. The severity of a fire is dependent upon many parameters that are beyond the control of the building designer, especially when one considers the range of terrorist threats that are possible. The performance in a fire of non-structural elements such as walls and ceilings is directly linked to the structural integrity of the building because a collapsed wall, ceiling, or floor exposes more areas of the building to the fire while providing additional fuel and air upon which the fire can feed. The technical basis for accurate measurement methodology and simulation tools for the inclusion of fire resistant properties of walls and ceilings in performance-based fire safety design is being developed under this program.

Improving Emergency Egress and Access—By working with the primary stakeholders (elevator and construction industries, fire services, professional societies, and code making bodies), the role of elevators in providing access by the fire service to a fire in a high rise building is being greatly enhanced over current practice. The development of hardened fire service elevators and new emergency operation procedures/controls will also lead to improved egress capabilities from tall buildings, especially for mobility-impaired or injured occupants. However, the behavior of people in an emergency situation has been altered in unpredictable ways by the events of 9/11. Current egress models may be inappropriate and/or insufficient for the design and placement of doors and stairways and the control of elevator movement. Behavioral and engineering studies are being conducted, drawing on experts in academia and elsewhere, to enable the development of simulation tools that better capture the movement of people within a building under fire and other emergency situations.

Developing Building and Emergency Equipment Standards and Guidelines—Partnering with other federal agencies and American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE), NIST-developed indoor air quality (IAQ) simulation tools are being extended to analyze and guide the assessment and subsequent reductions in the vulnerability of buildings to chemical, biological, and radiological aerosols. Standard building information models that facilitate the simulation of building system behavior during adverse events are being developed to allow communication among IAQ controls and other building controls associated with, for example, security, transportation, energy, and fire alarm systems. A user-friendly tool is being developed for building owners and managers to aid in the selection of cost-effective strategies for the management of terrorist and environmental risks. Also, facilities are being established for science-based exposures for measurement of firefighter equipment performance attributes essential to support informed fire service procurement decisions.

3.3 ACCOMPLISHMENTS OF WTC R&D PROGRAM

Prevention of Progressive Collapse

Buildings that are designed according to modern building codes are not expected to collapse during their service life period. They are designed typically to resist traditional governing vertical loads and lateral loads such as wind and earthquake. This situation is changing, however, due to an increase in deliberate terrorist attacks. In general, a terrorist attack may lead to failure of a small part of a building. When an initial local failure causes the loss of gravity load capacity in the structural frame, the failure spreads from story to story, which may lead to the total collapse of an entire building or a disproportionately large part of the building. This type of collapse is defined as "progressive collapse" (see Fig. 3–1). At present, U.S. building codes do not provide explicit provisions to enhance the resistance to progressive collapse. In terms of magnitude and probability of occurrence, the traditional vertical and lateral design loads are quantifiable. In contrast, terrorist loads are difficult to quantify as to size, location, and the nature of the loads. Terrorist attacks may include thermal, impact, or blast loads. Thus, in order to improve resistance to progressive collapse, U.S. building code developers have attempted to incorporate into the codes structural redundancies by introducing prescriptive requirements for "structural integrity." Changes are needed in the way buildings are designed and constructed so that resistance to progressive collapse is provided explicitly. Following the 2002 National Workshop, NIST is working jointly with the Multihazard Mitigation Council of the National Institute of Building Sciences and industry experts to produce a "Best Practices Guide" for mitigating progressive collapse of buildings for design professionals. This document will be published in FY2004. Subsequent research efforts will focus on the development of tools to assist design professionals in the design of new buildings against progressive collapse and methods to enhance the resistance of existing buildings to progressive collapse.

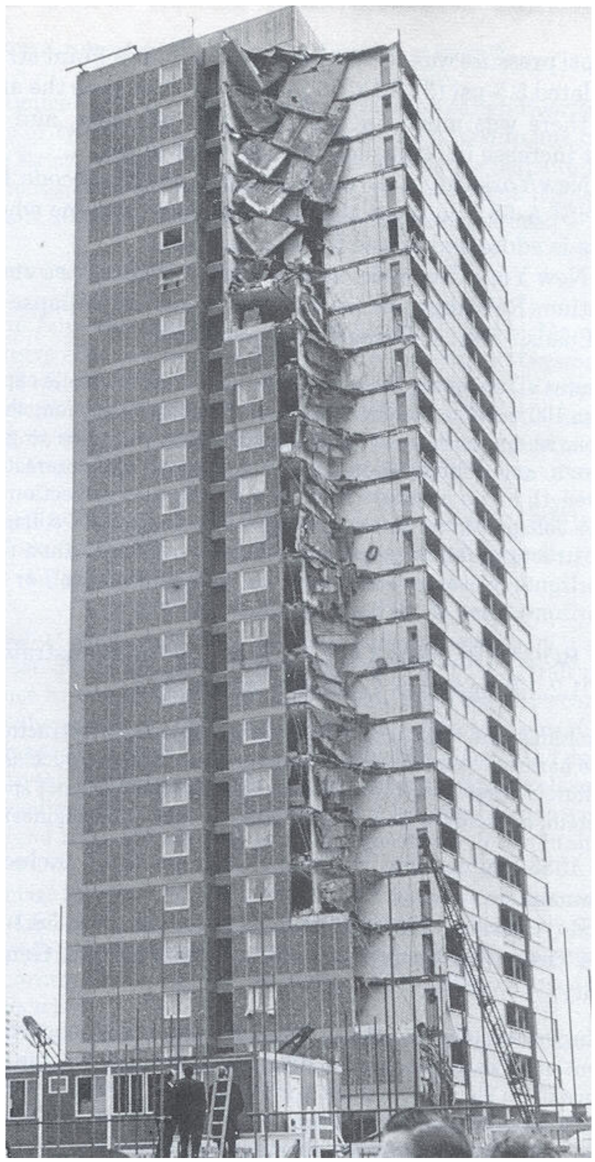

Figure 3–1. Ronan Point Collapse in 1968.

Fire Safety Design and Retrofit of Structures

Current building design practice does not consider fire as a design condition to predict and evaluate structural performance in the presence of an uncontrolled fire. Instead, fire endurance ratings of building members, derived from standard fire endurance tests, are specified in building codes. At the present time, there is no accepted science-based set of verified tools to evaluate the fire performance of entire structures under realistic fire conditions. Thus, there is an urgent and critical need to develop and implement verified and improved standards, technology, and practices that explicitly consider structural fire loads in the design of new structures and the retrofit of existing structures. A workshop was held recently in cooperation with the Society of Fire Protection Engineers to assess current fire safety practice and existing codes and standards, and to identify research gaps for an improved fire safety design and retrofit approach. The workshop was attended by national and international fire safety experts and provided the technical basis for the development of a national R&D roadmap for Fire Safety Design and Retrofit of Structures.

In addition, an evaluation has been performed of state-of-the-art numerical tools, including ANSYS and SAFIR, to assess their suitability for use in analyzing performance of structures under the combined fire and mechanical loadings. The evaluation process of these analytical platforms, which are rarely used in practice for fire safety design, is ongoing and necessary due to the complexity of structural systems, loading conditions, boundary conditions, and the highly nonlinear nature of material and structural behaviors. The effect of high thermal loading on structural performance of tested concrete columns, WTC steel connections, members, and subassemblies was examined. To better inform the modeling effort, a series of large-scale tests were conducted of steel components in a fire environment (see Fig. 3–2 and Fig. 3–3). The tested components included steel rods, columns, and open-web steel joists that were either left bare or had sprayed-on fire protective insulation material of varying thickness. Test fires were generated using liquid hydrocarbon fuels to produce medium-soot fires and high-soot fires, and the tests were continued until the temperature at any steel surface approached approximately 600 °C.

Figure 3–2. Insulated steel trusses, steel rod and steel column inside the NIST large-scale fire laboratory.

Figure 3–3. View of fire compartment from air exhaust outlet several minutes after the start of a fire test. Note: the flame impingement on the steel trusses and bar.

Fire Resistant Steel

Structural steel loses strength at building fire temperatures, leading to the need for fireproofing (see Fig. 3–4). Fireproofing adds costs and can be damaged or removed from the structure in a blast situation or unanticipated impact. In contrast, a new class of fire-resistant steels is specifically designed to retain more of the design strength at high temperature. These steels are being produced in Japan and Europe, and are now in use, either with or without additional fire protection. The use of fire-resistant steels leads to cost savings and schedule benefits during construction when application of fire protection can be avoided, and enhanced performance when protection is applied in the case of damage to the insulation. Unfortunately, the benefits of fire-resistant steel are not adequately tested under the standard U.S. structural fire standards (ASTM E 119), and thus, are not currently used in the U.S.

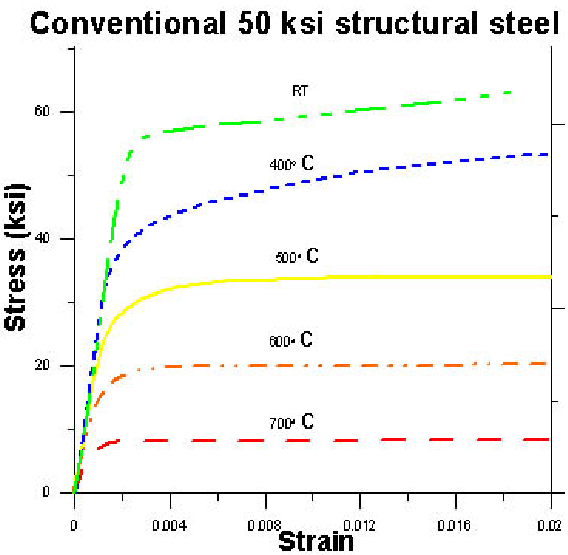

Figure 3–4. Stress-strain curves of a conventional structural steel, showing degradation of properties at high temperature.

A project has been initiated to ascertain which properties of steel are critical for efficient use of fire-resistant steels, such as high temperature strength and creep (see Fig. 3–5). Conventional steels and fire-resistant steels are being characterized to determine these critical properties. Our goals include both provision of accurate data on fire-resistant steels and development of quick and accurate tests for measuring relevant high temperature properties.

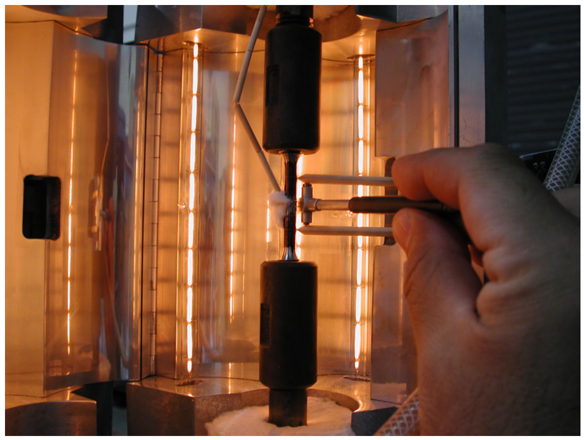

Figure 3–5. High temperature tensile tests to measure performance of structural steel at temperatures found in building fires.

Methodology for Fire Resistance Determination

Compartmentation is the cornerstone of limiting room-to-room and building-to-building fire spread. Standard fire resistance testing of wall/floor/ceiling assemblies provides an indicator of fire resistance and has proven valuable over time. However, these procedures have significant limitations that restrict their value for performance-based design and especially for high-risk occupancies. These limitations include: (a) standard time-temperature curves that may not be sufficient for all threats; (b) uniform heating, while many fires produce hot spots that may make the tests non-conservative; (c) single point thermal measurements; (d) pass/fail criteria, which make adaptation to other fire scenarios difficult; (e) documentation of the initial failure mode, but not the relative time to any successive modes, and (f) relative ratings, not absolute values.

Compartmentation is especially important in tall buildings, where the egress of numerous occupants can be a complex process, and barriers to the spread of flame keep the egress paths open, extend the time available for escape, and increase the safe time in places of refuge. For all these functions, it is necessary to know, in terms of real time, how long the interior partitions in a building will contain flames and smoke.

NIST has embarked on a course to provide such a methodology for inclusion in performance-based design of buildings. The research involves obtaining real-scale experimental data, modeling the behavior of partitions as they are driven to failure by fire, and developing recommendations for obtaining the input parameters from modifications of standard fire resistance tests such as ASTM E 119 and ISO 834. The initial work will focus on non-loadbearing walls of gypsum panels and steel studs, the most common interior construction in tall buildings. A continuing effort will extend the research to glass-panel walls.

The modeling effort will be done in three steps. First is a simple model for failure, beginning with crack initiation and propagation, continuing to the supporting structure, and finally to the fasteners and their failure points. This is now underway. The second component will be development of a detailed model of the partition materials to ascertain what additional data need to be obtained from the test method. The third component is development of a detailed model of a partition assembly for use by building design and engineering firms.

A series of real-scale compartment tests is providing information on the phenomenology of partition response and failure and also quantitative information to guide the model development (see Fig. 3–6). Various wall assemblies 2.44 m x 2.44 m were exposed to intense fires from the time of ignition to beyond flashover. Flux meters provided time histories of the energy incident on the walls. Thermocouples and infrared videos provided data on the transport of heat through the walls and on the progress toward perforation.

Figure 3–6. NIST measured the thermal behavior of gypsum/steel wall assemblies subjected to severe fire conditions.

Emergency Use of Elevators

This project is aimed at the development and implementation of protected elevators that can be used for fire department access and occupant egress during emergencies in tall buildings. The general strategy is to first incorporate into U.S. codes and standards a protected elevator system for fire department access. These are known in other countries as firefighter lifts, and there are existing requirements for these in at least 12 countries (as identified in a report by ISO TC178 on Elevators and Escalators). Once the U.S. fire services are satisfied that elevators are safe and reliable during fires, codes and standards would be changed to recognize protected elevators for occupant egress, secondary to, or integrated with, stairs.

The key technological advancement offered in the NIST strategy is the (new) concept of remote manual control. Here, the elevator system safety is monitored in real time by the fire alarm system and displayed on a standardized fire service interface developed jointly by NIST and the fire alarm industry, through the National Electrical Manufacturers Association (NEMA) and implemented in the 2002 edition of the

National Fire Alarm Code (NFPA72). This system addresses residual concerns held by the fire service and elevator industry even where such systems are utilized under existing codes and standards. The system might be further specified for accessible elevators required in U.S. and other building codes for access by people with disabilities but where the safety for use in egress during fires is still considered questionable.

Several technical papers have been written by NIST and presented at a recent international conference on Tall Buildings organized by International Council for Research and Innovation in Building and Construction (CIB) and Council on Tall Buildings and Urban Habitat (CTB&UH). NIST organized and chaired the speakers' session on emergency use of elevators, which included papers by two of the largest U.S. elevator companies (Otis and Kone). NIST also co-sponsored and presented papers at a workshop in March 2004, organized by American Society of Mechanical Engineers (ASME) and their A17 committee, who are responsible for the standard convening the safe use of elevators referenced in all U.S. building codes. NIST is working with the key representatives of the elevator industry and regulators represented on the A17 committee and with the product development engineers at Otis and Kone to implement the required technology and interfaces into their elevator controls, and on a novel approach to work out changes to the elevator control software for emergency operations protocols during fires. This approach would utilize NIST Virtual Cybernetic Building Testbed (VCBT) to allow numerous simulations of building fires to test the ability of the control software to adapt to conditions and to maintain safe operations.

Workshop on Building Occupant Movement During Fire Emergencies

NIST, in cooperation with the United Technologies Research Center, hosted a 2-day workshop focusing on the needed research on occupant behavior and movement during building emergencies. This workshop was motivated by a renewed interest in how buildings should be evacuated during fire emergencies and by the desire to provide a forum for the exchange of experiences among the fire and non-fire communities working on emergency egress. Sessions were held on codes and standards requirements for building evacuation, data needs for predictive building movement models, building movement strategies, and a roundtable discussion among selected government agencies. Participants included national and international experts in building occupant movement, representing the academic, consulting engineering, building products, and codes and standards communities. An outcome of the workshop will be the identification of areas where research is needed most to aid government agencies, industry and academic researchers in prioritization of their resource investments.

Guidelines and Technologies for Mitigation of Chemical, Biological and Radiological Aerosol Attacks

The increased attention to the potential vulnerability of buildings to airborne chemical, biological and radiological (CBR) agents has led to the need for better simulation tools to evaluate the transport and fate of such agents in buildings. NIST's longstanding expertise in airflow and contaminant transport modeling in buildings systems has been employed in many such analyses, and recently these capabilities have been extended via the release of version 2.1 of the CONTAM software. Among other enhancements, CONTAM is now able to use the output of exterior plume models as an input, such that outdoor contaminant concentrations from an exterior agent release can vary as a function of opening location on the building façade and time. This new capability allows users to link their exterior transport models to CONTAM and allow detailed analyses of the impact of an exterior release on indoor concentrations. In addition, CONTAM version 2.1 has improved models of particulate contaminants and has added fan and damper transients to the ability to simulate controls. The updated CONTAM model is now being used by an increasing number of researchers and practitioners in their evaluation of specific buildings and of technologies with the potential to increase building protection (see Fig. 3–7).

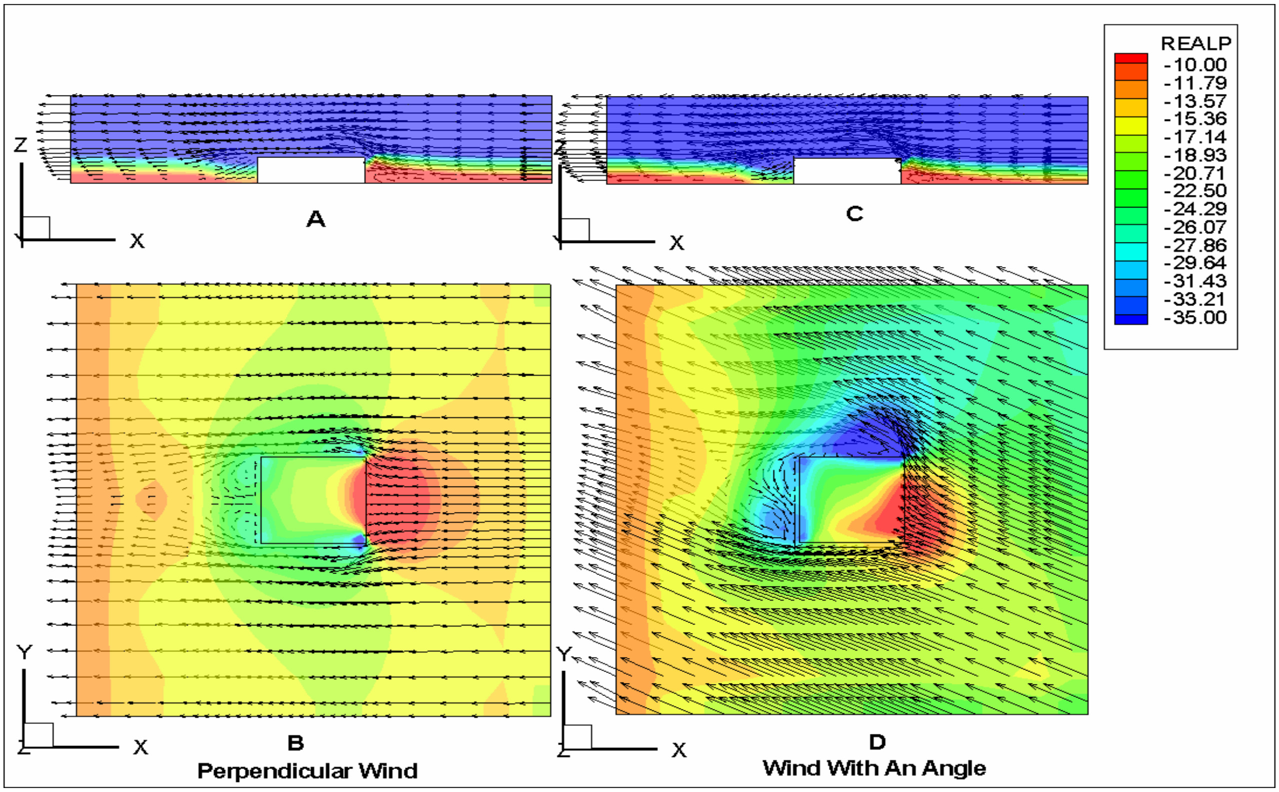

Figure 3–7. Exterior flow field as input to CONTAM model of building.

Cost-Effectiveness Tool for Managing Terrorist Risks in Constructed Facilities

Owners and managers of constructed facilities are faced with the task of responding to the potential for future terrorist attacks in a financially responsible manner. An economic tool is needed to direct limited resources to investments in mitigation strategies that will provide the most cost-effective reduction in personal injuries, financial losses, and damages to buildings, industrial facilities, and infrastructure.

The economic tool under development by NIST is a decision methodology, embedded in user-friendly, decision-support software, that helps building/facility owners and managers choose the most cost-effective mix of mitigation strategies. Three mitigation strategies are considered: (1) engineering alternatives; (2) management practices; and (3) financial mechanisms. The economic tool will provide decision makers with the basis for generating a risk mitigation plan that responds to the potential for future terrorist attacks in a financially responsible manner.

Early in 2002, NIST prepared a white paper outlining the tool development effort. NIST used the white paper to solicit stakeholder inputs, create opportunities for collaborative efforts, and form a technical working group of individual external subject matter experts. This has resulted in collaborative efforts with the Wharton Risk Management and Decision Processes Center, the Construction Industry Institute, ASTM International, and the U.S. Environmental Protection Agency. Safe Buildings Program. An expanded version of the white paper entitled "Economic Approaches to Homeland Security for Constructed Facilities" was delivered at the September 2002 CIB Meeting in Cincinnati as the invited Keynote Address.

Significant recent products include a prototype version of the software and a NIST Internal Report illustrating the methodology via a case study building. The prototype version of the software was completed and presented to the Steering Committee in September 2003. The prototype includes the software's graphical user interface and linkage to database files and key reports. The beta version of the software is planned for completion in 2004; it will facilitate a variety of user-specified analyses. All analyses employed in the software will be consistent with ASTM standard practices. A case study report illustrating how to apply the life-cycle cost method (ASTM E 917) to a prototypical commercial building renovation project was published in NIST IR 7025. A subsequent technical report documenting the decision methodology is planned for publication in 2004.

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