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Analysis Tools and Guidance Documents for Evaluating and Reducing Vulnerability of Buildings to Airborne Threats—Part 1: Literature Review

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ABSTRACT

This paper classifies and describes analysis methods, tools, and simulation programs that allow prediction of airborne chemical/biological dispersal and transport dynamics in indoor environments subject to different risk scenarios. These are the building blocks for related analytical treatment of the overall problem involving risk assessment, risk management, and identifying cost-effective mitigation measures. These methods are distinguished by the level of mathematical and scientific rigor in modeling the phenomena, in the spatial and temporal resolution in solving the modeling equations, and in the types of boundary conditions and the numerical parameters that appear in the model. The paper also describes various general guidance documents and vulnerability assessment protocols and software available in the open-source literature to assess and reduce vulnerability in buildings due to airborne threats and risks.

INTRODUCTION

Assessing and reducing the vulnerability of buildings to airborne chemical and biological (CB) threats has been the subject of major and numerous efforts in the last decade, and has resulted in a large body of published knowledge. This paper reviews the existing open-source literature, available protocols, and analysis tools in order to classify them in terms of scope of applicability and state of development. The literature review is not meant to be exhaustive, but every effort has been made to identify representative and unique material. This paper starts with a classification of analysis methods, tools, and simulation programs that allow analytical prediction of airborne chemical and biological agent dispersal and transport dynamics in indoor environments subject to different risk scenarios. This is followed by a more general screening of documents, protocols, and software that practitioners can use to evaluate the vulnerability of buildings and improve the security of occupants.

BUILDING VULNERABILITY ANALYIS TOOLS

This section classifies and describes analysis methods, tools, and simulation programs that allow analytical prediction of airborne CB dispersal and transport dynamics in indoor environments subject to different risk scenarios. These are the building blocks for related analytical treatment of the overall problem involving risk assessment, risk management, and identifying cost-effective mitigation measures. These methods are distinguished by: (1) the level of mathematical and scientific rigor in modeling the phenomena, (2) the spatial and temporal resolution in solving the modeling equations, (3) the types of boundary conditions and the numerical parameters that appear in the model, and (4) the degree of specificity, i.e., the tool may not have been developed for risk analysis purposes per se but could be used for vulnerability analysis if the simulation results are analyzed external to the tool; for example, the CONTAM program developed by National Institute of Standards and Technology (NIST) (Walton and Dols 2008).

Compartmental Models

Compartmental modeling is a special type of linear system modeling that is well developed and has had some success in the fields of biomathematics and environmental and chemical engineering. Godfrey (1983) defines a compartmental system as consisting of “a finite number of homogeneous well-mixed, lumped subsystems, which exchange with each

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other and with the environment so that the quantity or concentration of material within each compartment may be described by a first-order ordinary differential equation (ODE)." This formalism of compartmental modeling is particularly appropriate for preliminary "what-if" studies and for calibrating models against limited and sparse direct concentration-measurement data (Evans 1996a, 1996b). It can provide insights into issues of problem identification, such that the design of field measurements can be suitably tailored as a result. On the other hand, compartmental modeling provides limited detail in terms of spatial concentration distribution. Finally, the numerical values of the model parameters appearing in the equations, which are to be viewed as lumped parameters, have to be determined with care. The set of modeling equations can be compactly formulated in a state-space representation. Depending on how one solves this set of equations, one can distinguish between three different approaches applicable to the context of airflows in buildings.

1. *Closed form analytical solutions* can be determined for a number of practical one-zone and two-zone building scenarios. In addition to computational simplicity, they allow convenient model parameterization, which is very useful for model calibration using field data, allows uncertainty analysis to be performed easily, and provides insight into which physical parameters need to be measured with more accuracy (Reddy and Bahnfleth 2007).
2. *Spreadsheet programs* can be used to simulate air and contaminant flows by reducing the number of zones in a building to a small, manageable number of aggregated well-mixed zones. Such a representation may be adequate for assessing the vulnerability of building occupants to inhaled dose (Kowalski 2003). The rationale for the simpler approach is that well-defined boundary conditions (necessary for detailed engineering simulation) are hard, if not impossible, to characterize practically, given that event scenarios have large uncertainty and variability. Further, the spreadsheet simulation approach allows calibration to be achieved with relative ease, in addition to which parametric and sensitivity analyses can be performed in a straightforward manner.
3. *General-purpose building simulation programs* generate numerical solutions for, in effect, as many zones as one wishes. The most common programs are CONTAM (Walton and Dols 2008), RISK by the Environmental Protection Agency (EPA), and COMIS by Lawrence Berkeley National Laboratory (LBNL 2003). Lorenzetti (2002a) assesses several multizone software, while computational aspects are reviewed in Lorenzetti (2002b). Such multizone models provide information about the dynamic behavior of room average indoor concentrations at a considerable reduction in computational effort as compared to the detailed CFD modeling approach. Effects such as infiltration due to stack and wind pressure differences; interzonal flows through walls, doors, and windows; and stack effects in stairwells and elevator shafts can be explicitly considered. Note that in IAQ-relevant studies, it is not simply the air within the space that is treated as a compartment, but floors, carpets, drapes, HVAC ducts, and other components with which indoor pollutants can interact are also modeled as compartments. Shortcomings of this approach are that it cannot model zones that are poorly mixed, nor can it capture bidirectional and vertical stratification effects. As a result, occupant exposure levels predicted by these models are room-average values that may be under or above actual exposure levels. These models have been extensively used for building-related analysis involving both design and performance evaluation (e.g., Musser and Persily [2002]; Persily et al. [2007]), as well as for assessing the casualty impact from biological agents (Kowalski and Bahnfleth 2003). The effort involved in modeling the building and then calibrating it against monitored data is time consuming, with the latter aspect still an area of active research (e.g., Price et al. [2003] and Firrantello et al. [2005]).

Detailed Deterministic Simulation Programs

Reports by Stenner et al. (2001) and Sohn et al. (2004) identify current simulation models for determining dispersion and migration of CB agents within and around the exterior of buildings, and review the capabilities and limitations of selected models. Sohn et al. (2004) suggested a classification scheme of existing simulation software, which is modified into the grouping as follows:

1. *Computational fluid dynamics* (CFD) models give detailed, if not always accurate, predictions of the fate and transport of CB agents in HVAC systems and of the spatial concentration distribution in the room/building under well-defined boundary conditions. Several commercial software packages can be used; however, Airpak by ANSYS Inc., Flovent by Flometrics Inc., and FEM3MP by Lawrence Livermore National Laboratory (LLNL) are especially meant for simulating air and pollutant transport within the built environment.
2. *Real-time dispersion-deposition-causality models* (also referred to as *operational models*) have been developed for use by emergency managers, battle commanders, and building designers and maintenance personnel to limit the loss of life in simulating hazardous material release scenarios over regional scales of 1 to 100 km. They link real-time weather data, topological data, dispersion modeling, and population data to the resulting population exposure level. These models are based on statistical dispersion methods rather than on fundamental fluid flow equations, and use 10 × 40 m grid cell resolution. Sohn et al. (2004) list a dozen such programs, and discuss a few in some detail.

3. *Environmental regulatory models* are also unsuited for IAQ modeling but are meant for the prediction of hazard migration in the outdoor environment. These require terrain depiction, modeling of vertical and horizontal turbulence, atmospheric convective mixing, and modeling of aerodynamic effects. Sohn et al. (2004) provide a list that includes 7 preferred models, 10 simplified screening models and 34 alternative models, all of which are meant for environmental regulatory purposes. AERMOD by USEPA is considered the most accurate regulatory model available. Typical spatial area suited to these programs is 1 × 100 k, with 1 m numerical grid resolution. The bibliographic report by Chapman and Thomas (2007) also discusses a number of software tools.

Probabilistic Modeling and Simulation Programs

The previous two groups of analysis methods of analyses were deterministic in their approach in that all inputs to the model were characterized by single values (presume known without any uncertainty). The usual manner to study the effect of uncertainties on the system response using such tools is to perform a sensitivity analysis. This is generally done in a somewhat ad-hoc manner, involving only parameters selected by the user and with deviations from baseline values selected somewhat arbitrarily. However, there is an alternative approach, called *probabilistic* or *stochastic modeling*, where the uncertainties are treated in a more structured manner and which is more appropriate for risk-based modeling. In essence, the inputs are assumed to be random variables and are represented by probability distributions rather than point estimates.

Numerous sources of uncertainty surrounding the issue of developing assessment protocols for enhancing the security of buildings *vis-à-vis* indoor-related IAQ threats have been pointed out by Kunreuther (2002) and Reddy and Bahnfleth (2007). These include (1) uncertainties in the probability of occurrence of an "extreme IAQ event"; (2) in framing the boundary conditions and in the input parameter specifications; (3) accuracy of the system behavior prediction; (4) of the dose-response relationship for the particular CB agent; (5) the validity of the consequence function to the owner; and (6) the cost uncertainty associated with implementing the necessary mitigation measures identified. Given the above uncertainties, it is appropriate to review some probabilistic modeling software that is commercially available. One can distinguish between the two following types:

1. *General-purpose risk analysis* software is available in two platforms: add-on and stand-alone. Crystal Ball (Decisioneering Inc.) and @-Risk (Palisade Corp.) are perhaps the most widely known add-on software for spreadsheet programs (which allow forecasting and optimization to be done along with risk analysis) and adopt Monte Carlo simulation by which to generate numerous trials. GoldSim (2005) is an example of stand-alone software that allows complex analyses and modeling to be performed. It is a highly graphical, object-oriented simulation platform suitable for performing dynamic, probabilistic simulations to support management and decision making in engineering, science, and business. Another versatile modeling and simulation platform for assessing risks in macro-environmental effects (which include ambient air fate and transport models, water-borne fate and transport models, dose response models, etc.) is the Framework for Risk Analysis in Multimedia Environmental Systems (FRAMES), developed by Pacific Northwest National Laboratory (PNNL) (Sohn et al. 2004). FRAMES is not a modeling and simulation tool as such, but a software interface structure that allows legacy models, databases, and software from disparate sources to communicate in a plug-and-play manner. Not only does it allow data transfer between different specialized programs, but it also has a suite of tools for integrating, analyzing, and visualizing data, and for performing sensitivity and uncertainty analyses.
2. *Specialized software*, of which GoldSim's "Contaminant Transport Module" is particularly appropriate for understanding and predicting the migration of mass (e.g., contaminants) in environmental systems. This is an extension of GoldSim (2005), which allows convenient modeling of the release, mass transport, and fate of materials and pollutants within complex environmental systems.

Chapman and Thomas (2007) have identified a large number of resources, both in the form of reports and software tools, on hazard identification (both natural and man-made), risk assessment, and risk management software. Some pertinent risk reduction guidance and protocols available in the open literature are described in the next section.

FULL-RISK ASSESSMENT PROCEDURES

This section covers assessment procedures and software meant to provide a full-risk evaluation of security so as to reduce vulnerability of existing buildings and other infrastructures.

1. An important methodology or framework (or guide) specially meant for analyzing and managing risks associated with terrorist attacks on critical infrastructures is ASME's RAMCAP (ASME 2005). RAMCAP, which stands for risk analysis and management for critical asset protection, allows an asset-level and system-level risk analysis and management to be performed. It is designed specifically to assist private sector owners and operators of infrastructure assets to perform risk management for internal decision-making purposes. This methodology has been applied to date to the following sectors: nuclear power plants, nuclear spent fuel storage and transportation, chemical manufacturing plants, petroleum refiner-

ies, LNG terminals, dams, and wastewater treatment systems. These specific sectors are relatively narrow and most of the relevant information is available. Whether such a framework will ever be extended to commercial building is uncertain because of their diversity and lack of clear vulnerability metrics.

2. FEMA is an authoritative source of information that has released several publications collectively referred to as the Risk Management Series that deal with such risk assessment, management, and mitigation and design issues especially applicable to buildings. These include FEMA 426 (2003a), FEMA 427 (2003b), FEMA E155 (2004), and FEMA 452 (2005). The risk assessment process model involves the following five steps: (1) threat identification and rating wherein the threat is identified, defined, and quantified; (2) asset value assessment, which involves identifying the value of the building's assets that need to be protected; (3) vulnerability assessment where one evaluates the potential weaknesses of the critical assets against a broad range of identified threats and hazards (this step provides a basis for determining mitigation measures); (4) probability of occurrence in order to ascertain risk level for each asset against each threat (usually, one obtains a relative risk profile since absolute probabilities of different occurrences are hard to define; this allows prioritization of resources); and (5) risk management where one considers and ranks different mitigation measures on their risk level reduction potential, with the final selection for implementation being based on cost effectiveness.

   Each of these assessments consists of a series of subgroups of questions. Answers to these questions allow a rating metric to be determined. The building vulnerability assessment checklist consists of a series of questions that are embedded in a software program with a database. The questions are grouped into the following broad categories: site (23 questions), architecture (28 questions), structural systems (11 questions), building envelope (5 questions), utility systems (22 questions), mechanical systems (22 questions), plumbing and gas systems (6 questions), electrical systems (7 questions), fire alarm systems (5 questions), communications and IT systems (16 questions), equipment operation and maintenance (8 questions), security systems (48 questions), security master plan (15 questions). A risk assessment rating index matrix is determined for each of these categories. Pertinent guidance documents specific to each question are also provided. This document (and associated software) is perhaps one of the best ones available among published literature.

   An advantage of this tool is that several assessors can use it at the same time. Various assessors with different specializations can answer the questions provided in the FEMA 452 appendix that apply to their specialization. The information in these assessor databases can then be linked to a master database that collects all the information. In terms of a vulnerability analysis, this program combines two features—risk matrices and an assessment checklist. The two matrices generated in this program are a critical function matrix and a critical infrastructure matrix. The matrices list the various critical functions and critical infrastructures (which can be user-defined) versus different attack scenarios. For each combination of function/infrastructure and attack scenario, the user specifies a threat rating, an asset value, and a vulnerability rating (all 1–10) based on the scales described in the FEMA 452 document. The program then calculates a risk rating and color-codes it by the level of risk. This provides a measure of the building's vulnerability and risk to various attack scenarios. A limitation of the FEMA matrix approach is that it is difficult to rationally assign realistic weights for the various categories.

   The two threat matrices and the various assessment checklists lead to a complete vulnerability analysis of the building. However, determination of the threat ratings, asset values, and vulnerability ratings from FEMA 452 is quite subjective. Also, assessors who are experts/educated in their pertinent areas are needed. Further, this program only provides general guidance that is associated with each question regardless of the answer. Finally, this program is fairly complex to use and requires a significant amount of time to collect all the data that need be input into the database.

3. A subsequent improvement to the FEMA tool is the Building Security Council's (BSC) Building Security Rating System (BSC 2008). This is a rating system similar to that of the United States Green Building Council (namely, the LEED rating system) except that it rates building security rather than building sustainability. It builds on the FEMA threat matrix approach but provides specific recommendations as to how to assign numerical values to the various categories. The BSC's rating system finally provides a similar measure to LEED called "building security."

4. ASHRAE (2003) has a chapter on risk analysis that, though referred to as "Risk Management," does, in essence, cover the various aspects of risk analysis described in the FEMA procedure. This report is contemporaneous with, or even precedes, the FEMA manuals. It is broken up into four steps: (1) a "risk analysis" step, which is really risk assessment as defined in the traditional literature (i.e., determining exposure level, identifying risks, estimating probability of occurrence, and, finally, determining value of loss); it covers steps 1–4 of the FEMA 452 (FEMA 2005) guide; (2) "risk treatment planning," which is, in essence, similar to step 5 of the FEMA 452 guide; (3) risk treatment plan implementation, which involves framing a coherent plan to install and commission the measures identified in the previous step; and (4) reevaluate the plan after implementation and

modify as needed. Each of these steps can be performed either on subjective (or heuristic) or objective (or based on analytical) methods. ASHRAE (2003) provides guidance for new and existing buildings regarding health, safety, and environmental security under extraordinary events. The document discusses characteristics and attributes of buildings that make them susceptible to threats, as well as specific measures to make them less vulnerable (relating to outside and inside building access security measures, changes to HVAC systems, personal protection, management plans in place, etc.). The recommendations of this report have been revised and expanded in a recent report (ASHRAE 2009). A complete risk management example of how to implement the exposure level matrix approach is given. The document also provides a life-cycle cost analysis and discusses how to create a risk mitigation plan. The downside of this tool is that it is almost entirely user defined, which makes it very subjective since the assignment of category levels and weights is on a relative scale and subject to some personal interpretation. It also does not provide any type of questionnaire that an assessor can follow.

5. The report prepared by the National Research Council (NRC 1983) also addresses issues relevant to risk analysis, though not in the itemized structure adopted by the previous two documents. It includes a description of factors that influence the design and implementation of building protection measures, as well as tools pertinent to both new and existing building designs. The types of enhancement or mitigation measures one could adopt relating to HVAC systems, airflow distribution, air-cleaning systems, and HVAC zoning are also addressed. The critical need for proper installation and maintenance, as well as engineering issues relating to detection and identification technologies are discussed which involve types of sampling systems, their locations, detectors, identification systems, triggers, etc. Finally, the issue of developing operational response plans is addressed. Only after all the above-stated aspects have been described, does the report tie these elements into a framework consistent with formal risk analysis approach (risk assessment and risk management), which culminates into a discussion on the deployment and decision-making regarding resource deployment.
6. Sandia National Laboratory has developed a tool called the *security risk assessment and management (SRAM) methodology* (Sandia 2001), which, however, is restricted by the US government. It was first developed as RAM-D/T for hydroelectric dams and high-voltage transmission and, subsequently, applied to such infrastructure systems as bridges, buildings, tunnels, water systems, cities and communities, energy plants, etc. Certain organizations of GSA have also been involved in its applications for their federal buildings. The tool has been validated against actual buildings and facilities for many years. Of all the tools described earlier, several practitioners argue that SRAM is the only systematic security risk assessment approach developed for that specific purpose (addresses and integrates threats, consequences, and vulnerabilities, all in one risk methodology).

SCREENING TOOLS, CHECKLISTS, AND GUIDANCE DOCUMENTS

It was suggested (Bahnfleth et al. 2008) that one should distinguish between the following types of guidance depending on how they were reached, i.e., whether heuristic in nature or based on the following analytical procedures:

a. Threat assessment of the baseline or existing conditions (or screening the building for vulnerability): (1) *heuristic* or based on common sense or tacit knowledge of experienced professionals, and without explicitly computing risk; this is usually based on a questionnaire to be filled by the building owner or his representative; (2) *empirical* or a procedure based on some simple formulation of the risk function that involves combining heuristic weights with some broad measures describing the building's state of vulnerability; (3) *formal risk analysis* procedures. No widely accepted method exists for formal analysis of risk from airborne CB agents for building occupants.
b. Recommending specific retrofits to building and systems, and changes to current operations and maintenance (O&M) practices: (1) *heuristic* where the measures are based on field experience by professionals; (2) *semi-quantitative* where some simple cost benefit calculations have been performed; (3) *quantitative*, based on adopting a modeling tool specific to the building and adopting formal cost benefit analysis tools to identify measures.

A basic premise behind ascertaining a building's vulnerability is that there is no one single process or formula one can apply. One needs to consider a number of issues relating to existing conditions *vis-à-vis* key systems and security measures in place before one can suggest measures and retrofits to enhance occupant safety. It is not surprising that guidance protocols developed to date are fairly consistent and exhibit considerable overlap with each other since they have evolved from the same line of thinking and on shared sources.

1. The National Institute of Occupational Safety and Health (NIOSH 2002) (also described in Chapter 2 of Gustin [2005]). This was among the first documents to attempt to develop a list of items to be specifically considered in terms of airborne attacks. This is done by inspecting specific subsystems of the building that offer potential gaps in the building's security. These include mechanical condition of the equipment, type of air filtration system in place, proper functioning of the air dampers, control logic of the HVAC system, proper functioning of the VAV boxes, and others. Based on the results of this inspection, one can identify specific recommendations that fall in one of four broad categories: (1) things to do, (2) physical

security, (3) ventilation, or (4) filtration, maintenance, administration, and training. The list of inspection items is by no means complete and neither are the recommended measures exhaustive, but this was the first document based on which more sophisticated ones were subsequently developed.

2. A book by Kowalski (2003) discusses several issues relevant to immune building systems technology. Of special interest are two quantitative approaches to determine the time-weighted impact of an airborne biological attack using a spreadsheet program (for a building with a small number of zones at time intervals of one minute) and also using a multizone model such as CONTAM. Different types of buildings subject to some typical extreme event attacks are simulated by both methods, and he concludes that both methods yield very similar results. The book also proposes a heuristic metric to quantify the relative risk of a building and its occupants to CBW attacks.

3. The chemical/biological building protection tool (CBT) developed by UTRC (2004) is a "user-friendly" interactive program that gives a measure of the building's risk and vulnerability, makes recommendations for improvement, shows the effects of those improvements, and allows for a preliminary economic analysis. It is meant to be a screening tool to evaluate overall vulnerability of a particular building or facility to CB threats and to suggest risk reduction measures that should be investigated further. It is a software program that was intended for early stage building design and for the use of architects and building mechanical system designers. It was not meant as a tool to reduce building vulnerabilities, though one could use it as such. It is also restricted in its circulation by the US government. It is based on questionnaire responses provided by the user, and is in some ways similar to the FEMA document. The software allows the IAQ threat to be treated in terms of threat assessment (agent type, concentration, duration of release, method of release, probability of event, vulnerability assessment of building type, purpose, location, accessibility, protective plans, and measures in place), protective measures (improving HVAC system, strengthening exterior envelope of building, site protection, enhancing security, detection measures), and protective options (such as available resources, tolerance to change, time/urgency, cost/benefit). The software calculates an overall empirical rating measure for the various threat categories. However, it relies on precalculated events and heuristic consequences to provide the necessary information on implications of various threat assessments and the effect of potential design solutions, which are then analyzed as a whole to provide the necessary recommendations.

4. BVAMP (LBNL 2005) is a software tool specifically to assess building vulnerability to indoor and outdoor CBR attacks based on responses to a walk-through questionnaire relating to such factors as the building exterior, the roof, building entrances, the main lobby, the mail room, the garage and loading dock, stairwells, tunnels or skyways to other buildings, storage areas, hazardous materials storage, HVAC maintenance and utility rooms, HVAC system details, emergency response plan, building plans/drawings/documents, and general security measures. Once these questions have been answered, the assessor completes a software questionnaire that is broken into four categories of questions: (1) emergency response plan, (2) HVAC systems, (3) building access, and (4) HVAC controls. The software program frames each question so that they can be answered with simply a "yes" or a "no." Once all questions have been answered, a recommendations file is generated. Though building specific, the recommendations are still general recommendations, but are listed in order of cost of implementation. Therefore, this program allows for a qualitative and preliminary economic analysis. It also assists owners in improving emergency preparedness by suggesting building system control protocols for use during emergencies (such as shelter-in-place locations, purging mode, shutting down HVAC, etc.). However, no measure of risk is provided, nor a measure of how vulnerable the building is or how the building resiliency will improve, by implementing the given recommendations. Many of the suggestions, recommendations, and advice in this software tool in preparation of an attack are based on research documented in the report by Price et al. (2003).

5. Rhode Island Department of Health has developed a *Building Vulnerability Assessment Tool* (BVAT 2004) to assist building owners/managers in locating vulnerabilities of their AHUs in the event of an airborne biological attack, and ascertaining which protective measures to institute. The measures are also meant to improve overall IAQ and reduce occupants' exposure risk to commonplace contaminants. Questions are grouped into categories such as: type of ventilation system, AHU, air intakes, recirculation modes, mechanical rooms, filtration specifications, O&M practice, etc. Risk management practices in place are not covered.

6. The Los Angeles Public Health department has developed a building assessment checklist (BAC) (Fielding et al. 2006), based on public documents such as those by ASHRAE, LBNL, US CERL, EPA, and the U.S. Department of Homeland Security. A research report prepared by RAND (2005), specifically for the Los Angeles area, also serves as an underpinning to this questionnaire. The intent of this document is to provide a tool for building-related personnel to assess existing building features from airborne hazards introduced intentionally either outdoors or indoors. Questions relate not only to building system type and design but also to interior security measures (shipping/receiving, storage, etc.) and to risk management measures in place.

The BVAT and BAC tools are both simple checklist documents that assess the building through a questionnaire to be filled out by the building assessor and with recommendations in the form of generic responses. Each response to a question in the checklist is referenced to a corresponding guidance/recommendation in the appendix of the document. These tools allow for a written assessment of the building and can indicate where vulnerabilities exist in the building and what can be done to increase building resiliency to airborne attacks. These checklists can be considered "user friendly" due to the ease of use and the short amount of time needed to complete them. However, these checklists only provide general recommendations that are by no means building specific. Also, neither document provides a measure of the building risk or vulnerability or offers a cost analysis corresponding to the given recommendations.

The above documents are to a large extent generic in that, though the questionnaire allows site and building specific conditions to be considered, the assessment and the guidance is largely heuristic and based on generic building type. A small number of studies have focused on evaluating the impact of specific measures relevant to an individual building via simulation. A report by Persily et al. (2007) describes attempts to quantitatively ascertain the impact of different generic airborne CB threats (using CONTAM) and evaluate different mitigation options for two buildings in terms of their security enhancement and cost. The shortcoming of the approach used in this study is its reliance on relative reduction of exposure, not absolute measures of hazard level. Table 1 indicates the approaches taken by different guidance documents as per the grouping stated above.

SUMMARY

This paper summarizes existing knowledge on tools and guidance documents for reducing vulnerability of buildings from airborne threats as applicable to noncritical buildings targeted toward: (1) risk assessment procedures; (2) design methods, available technology, and existing guidance to enhance resiliency of new buildings as well as existing buildings; (3) an overall classification of the various analysis methods; and (4) published guidance, procedures, and protocols and on risk reduction. Process flowcharts, checklists, and software have been developed to assist in the process of evaluating building security (Bahnfleth et al. 2008). Most of these tools rely heavily on human judgment, and those that do not still require data that may be difficult or impossible to obtain in an actual application. Risk reduction procedures and guidance protocols published to date are fairly consistent with each other since, in many cases, they have evolved from common sources. Many documents suggest a risk management procedure or protocol that consists of several steps such as threat analysis, vulnerability analysis, and consequence analysis. While there is not standard structure, each protocol includes essentially the same steps.

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Table 1. Summary of Different Approaches Taken by Guidance Documents

References	Threat Assessment			Remedial Action		
	Heuristic	Empirical	Formal	Heuristic	Semi-Quantitative	Quantitative
NIOSH (2002)	X			X		
Kowalski (2003)		X				X
ASHRAE (2003, 2009)		X		X		
CBT (UTRC 2004)		X			X	
BVAT (2004)	X					
FEMA 452 (2005)		X		X		
BVAMP (LBNL 2005)	X			X		
BAC (Fielding et al. 2006)	X					
Persily et al. (2007)			X			X

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