Requirements for a Probabilistic Quantitative Relative Risk-Based Decision Methodology for Reducing Vulnerability of Building Occupants to Extreme IAQ Events

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ABSTRACT

The issue of assessing existing buildings in terms of their vulnerability to extreme man-made intentional threats has acquired great urgency in recent years. Several federal and professional agencies, as well as individuals, have been working on this issue, and a number of analytical methods and tools have been suggested and developed. The field has reached a level of maturity where it is now necessary to synthesize existing work and define the types of specific consensus and research areas that need to be studied from the buildings perspective. This paper starts by providing a background on work being done in terms of defining exposure thresholds, guidance documents, and vulnerability assessment software. Subsequently, a relative risk quantitative methodology is proposed that first entails performing a quantitative risk assessment of occupant exposure to certain pre-specified extreme chemical, biological, and radiological (CBR) event scenarios with pre-assigned relative occurrence probabilities. This is followed by evaluating the effectiveness of different counter-measures in order to frame a course of action in a decision analysis framework. This paper clearly delineates the various issues involved, evaluates ways to mitigate this risk, and points out which aspects need to be approached heuristically by broad consensus and which ones need technical/mathematical/scientific treatment. Finally, it is suggested that the extent to which the indoor environment is affected by the HVAC system of the building and the fact that one is more interested in an aggregate relative risk to the occupants could allow boiling down a mass of detail into one that is better handled by simpler mathematical methods. We demonstrate how an analytical treatment offers some unique advantages that would combine ease of calibration with actual measurements, with the power to quickly assess the effect of multiple scenarios and mitigation measures, as well as to study the effect of variability and uncertainty at various stages of the analysis. Simulation of a dormitory building is used as a case study to illustrate the advantages of the analytical approach.

BACKGROUND ON RISK ASSESSMENT

One of the most important shifts in environmental energy policy was the acceptance in the late 1980s of the role of risk assessment and risk management in environmental decision making (Masters 1991). Traditional risk analysis is viewed as involving three interrelated aspects:

- **risk assessment**, the characterization and estimation of potential adverse effects associated with exposure to hazards,
- **risk management** (or mitigation), the process of controlling risks or reducing their probability of occurrence by weighing alternatives and selecting appropriate action and also by putting in place response and recovery measures should an adverse phenomenon occur, and
- **risk communication** to the general public and concerned agencies.

In recent years, people have argued that the “firewall” between assessment and management is artificial and distorts the actual intent and thus should be eliminated (Kammen and Hassenzahl 1999). Another problem is that health and safety are moral sentiments (like freedom, peace, and happiness) and are not absolutes that can be quantified impartially. They are measured intangibly by the absence of their undesirable consequences, which are also difficult to quantify (Heinsohn and Cimbala 2003). This leads to much controversy even today from various stakeholders about risk assessment in general—skepticism from scientists about the ambiguous and uncertain dose-response relationships used, to certain...
segments of the population expressing overblown concerns, and other segments feeling that risks are overstated (Heinsohn and Cimbala 2003). However, the general scientific framework or methodology for evaluating risks in a quantitative manner is well established, with the issue of how best to apply/tailor it to the context or specific circumstance still being in varying stages of maturity. An important limitation is the lack of complete quantitative data needed to exercise the assessment models, along with the realization that such data may never be entirely forthcoming in many application areas.

Risk assessment involves identifying the sources and nature of the hazards (either natural or man-made), estimating the frequency of their occurrence (i.e., quantifying them through subjective or objective probabilities), and, finally, evaluating the consequences (monetary, impact on human life) were they to occur. Regardless of the type of potential loss, procedures that are meant to allow assessing building vulnerability can be grouped into three general categories: (1) qualitative, (2) empirical, or (3) quantitative.

Qualitative risk assessment procedures are based on common sense or tacit knowledge of experienced professionals, wherein guidance is specific to measures that can/ought to be implemented without explicitly computing risk. Generally, this type of heuristic approach is extensively used during the early stages of a new threat (such as that associated with recent extraordinary incidents). For example, in terms of building vulnerability to chemical, biological, and radiological (CBR) attacks, numerous guidance documents have been prepared by several federal agencies (such as USACE [2001], DoD [2002], NIOSH [2002, 2003], FEMA [2003] and others) and professional societies (such as AIA [1999], ASHRAE [2003], and NRC [1983]), which are reviewed by Bahnfleth (2004).

Empirical procedures are based on some simple formulation of the risk function that involves combining heuristic weights to some broad measures describing the building. For example, Kowalski (2002) outlines a method to quantify the relative risk of building occupants to the hazard of a CBR attack, which involves considering four separate issues (hazard level, number of occupants, building profile, and vulnerability), assigning weights between 0 and 100% to each of them, and deducing an overall weighted measure of relative risk for the entire building. Appendix C of the ASHRAE guidance document (ASHRAE 2003) also describes a multi-step process, which involves defining a building category (based on factors such as number of occupants, number of threats received, time to restore operation, monetary value of the building, etc.), assigning relative weights of occupant exposure, assigning point values for severity, determining severity level in each exposure category, and finally calculating an overall score or rank from which different risk reduction measures can be investigated if a critical threshold were to be exceeded.

Quantitative procedures are based on scientific and statistical approaches that have the potential of providing greater accuracy in applications where the hazards are well defined in their character, probability of occurrence, and their consequences. Several books have been written on this issue both in general terms (such as that by Haines [1998]) and for specific purposes (such as that by Haas et al. [1999]). Quantitative risk assessment methods are tools based on accepted and standardized mathematical models that rely on real data as their inputs. This information may come from a random sample, previously available data, or expert opinion. The basis of quantitative risk assessment is that it can be characterized as the probability of occurrence of an adverse event or hazard multiplied by its consequence. Since both these terms are inherently such that they cannot be quantified exactly, a major issue in quantitative risk assessment is how to simulate, and thereby determine, confidence levels of the uncertainty in the risk estimates.

Risk assessment has been applied to a diverse range of applications, such as engineering, business, public health, and more recently to buildings (an overview discussion is provided by Reddy and Fierko [2004]). In the area of buildings, there are three broad categories of threats: natural disasters, accidents, and man-made intentional acts. The last can again be subdivided into different categories depending on which building element they impact (such as civil structure, direct physical, etc.). In the wake of growing concern over man-made extreme event threats, several organizations (both federal and professional) have started to develop recommendations on issues related to how CBR agents affect the indoor environment and the occupants. The probability of the threat could be reduced by implementing managerial/operational procedures, while adverse impacts, should the threat actually occur, could be reduced by technological measures (such as filtration and UV systems) as well as emergency measures.

The basic premise in studies related to assessing building vulnerability is that there are criteria toward which we can strive, which may not be true or even feasible. A case in point is quantifying the building in terms of a single vulnerability index (such as the Building Protection Factor [BPI] suggested by Kowalski et al. [2003]). The current thinking among fire hazard assessment professionals (which is perhaps the most closely related field to extreme event IAQ) is that, since the data needs for the risk evaluation model are unlikely to be known with any confidence, it is better to adopt a relative risk approach, where the building is evaluated based on certain pre-selected extreme event scenarios rather than an absolute one (Bukowski 2006). This seems to be generally the approach adopted by ASHRAE (2003) as well, albeit in an empirical, rather than an analytical, manner. However, on the whole, the current status of criteria and methodology for computing the consequences of an extreme CBR event for occupants is far from fully satisfactory, as noted by Bahnfleth et al. (2006).

Thus, one needs to distinguish between four quantitative evaluation methods, all of which are based on “scenarios,” i.e., specific circumstances of building design, operational conditions, and events under which the building and its occupants are exposed to harm:

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1. The term “vulnerability” is loosely used by most people to imply “susceptibility to harm” or is used interchangeably with “risk.” However, later in this paper, we assign a specific connotation to it when using the term “vulnerability-based assessment.”
1. **absolute risk assessment**, where not only are the scenarios assigned absolute occurrence probabilities but an attempt is made to be as comprehensive as possible;

2. **hazard assessment**, which can be considered to be a subset of risk assessment, and where one does not attempt to be exhaustive in considering all scenarios or assigning occurrence probabilities to them but simply uses a subset of important and relevant scenarios and studies their adverse impacts (this is what seems to be done for fire regulation [Bukowski 2006]);

3. **generic vulnerability assessment**, where a risk level and a course of action are determined based on the dynamic response of indoor concentrations under different preselected hazard scenarios without selecting any CBR agent specifically (i.e., not having to assume a dose-response relationship); and

4. **relative risk assessment**, which combines elements of either 1 and 2 or 1 and 3 by assigning relative weights (reflective of their occurrence probability) to a preselected set of hazard scenarios assuming a preselected set of CBR agents. An overall score to the building and its occupants can then be determined. It is this approach that we deem most appropriate practically for assessing risk of building occupants to extreme IAQ events.

The objectives of this paper are:

- To provide a background on work being done in terms of defining exposure thresholds, guidance documents, and existing software.
- To propose a decision-making conceptual framework based on quantitative relative risk assessment of occupant exposure to extreme CBR events. The various issues involved are clearly delineated along with evaluation of ways to mitigate risk. Further, this paper distinguishes between aspects that need to be approached heuristically by broad consensus and those that need technical/mathematical/scientific treatment.

- To point out that the fact that one is more interested in determining an aggregate occupant risk index and evaluating how the indoor environment is affected by the HVAC system of the building. This could allow boiling down a mass of detail into one that is better handled by simpler mathematical methods (such as an analytical approach) that would combine ease of calibration with actual measurements. Such an approach could, subsequently, allow quick assessment of the effect of multiple scenarios and mitigation measures as well as allowing study of the effect of variability and uncertainty at various stages of the analysis.

### TYPES OF ASSESSMENTS

Several of the software tools developed recently for addressing general risk to buildings as well as IAQ risks to occupants from extreme events, are briefly described in Appendix A. It would be useful to the reader to place them in a proper context related to the overall problem. One needs to distinguish between different categories of assessing risks for building occupants, each with its own specific objectives. Several such categories are shown in Table 1 as an illustration. This list is not meant to be exhaustive but merely illustrative.

<table>
<thead>
<tr>
<th>Category Type</th>
<th>Alternative 1</th>
<th>Alternative 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase of building</td>
<td>Existing (retrofit evaluation)</td>
<td>Design</td>
</tr>
<tr>
<td>Type of building</td>
<td>Specific building</td>
<td>General building type</td>
</tr>
<tr>
<td>Building profile</td>
<td>High risk</td>
<td>Low risk</td>
</tr>
<tr>
<td>Type of event</td>
<td>Once in a lifetime (acute, rare, extreme)</td>
<td>Continuous exposure (chronic, occupational, background)</td>
</tr>
<tr>
<td>Stakeholder perspective</td>
<td>Financial perspective of owner</td>
<td>Public policy perspective</td>
</tr>
<tr>
<td>Scope of vulnerability assessment</td>
<td>Occupant-IAQ only</td>
<td>Overall building (structural, occupant-physical or IAQ, etc.)</td>
</tr>
<tr>
<td>Type of assessment</td>
<td>Qualitative</td>
<td>Quantitative</td>
</tr>
<tr>
<td>Scope of assessment</td>
<td>Screening (early evaluation)</td>
<td>Detailed assessment (identify specific protection measures)</td>
</tr>
<tr>
<td>Assessment based on agent reaction on occupants</td>
<td>Performance (measured or modeled data)</td>
<td>Engineering assessment (without monitoring or simulation)</td>
</tr>
<tr>
<td>Awareness of exposed population while threat is in progress</td>
<td>Aware</td>
<td>Not aware</td>
</tr>
</tbody>
</table>

Table 1. Different Categories of Assessing Risk for Building Occupants (The alternatives pertinent to this paper are shown in bold)
First, we need to distinguish between different categories—whether existing or new, whether applicable to a specific building or to a generic type of building class (such as federal or state buildings, hospitals, airports, train stations, etc.). Next, a focus on chronic or acute exposure effects, which have been quantified by assigning different allowable thresholds and the risks associated with them, must be selected. An acute effect is said to occur as the result of a single exposure, usually associated with rare and once-in-a-lifetime events (i.e., the individuals are exposed to a large dose over a short time period), while chronic effects result from repeated or lengthy exposures. Agencies such as EPA, OSHA, NIOSH, ACGIH, and ANSI have developed quantitative metrics such as PEL, TLV, MAC, REL (see list of any appropriate text for definitions and further discussion, for example, Heinsohn and Cimbala [2003]), which specify the threshold or permissible levels for short-term and long-term exposure. The bases of these metrics are similar in nature, but these metrics differ in their threshold values because they target slightly different populations. For example, NIOSH is more concerned with the workplace environment (where the workforce is generally healthier), while EPA’s concern is with the general public (which includes the young and elderly as well and longer exposure times).

NIOSH has developed TLV-C (threshold limit values-ceiling) guidelines for maximum chemical concentration levels that should never be exceeded in the workplace. EPA defines extreme events as once-in-a-lifetime, nonrepetitive, or rare exposure to airborne contaminants for not more than eight hours. Though only “chemicals” are mentioned, the definition could be extended to apply to biological and radiological events as well. Consequently, EPA formed a Federal Advisory Committee with the objective of developing scientifically valid guidelines called AEGLs (acute exposure guideline levels) to help national and local authorities as well as private companies and professionals and recommend mitigation measures. Unfortunately, this service industry lacks well-established guidelines and tools as how to do so (existing ones are discussed in this paper).

**ELEMENTS OF A RISK-BASED MODEL**

A conceptual, relative risk-based model, and one that applies equally to the specific problems at hand, requires several modules as shown in Figure 1. Each module either specifies a particular piece of the process or entails performing a certain analysis in furtherance of the final intention, which is to make a decision (of implementing a certain mitigation measure or else doing nothing). The functionalities of these seven modules are described below:

1. Considering the existing system or building would entail gathering information on such aspects as physical size (dimensions, height, number of floors, etc.), number of zones, number of occupants in each zone, activity of occupants, type of air distribution system, and physical parameters of the various components (ACH, outdoor air fraction, filter efficiency, etc.).

2. The threat (extreme event) scenario definition would involve such issues as type of CBR agent, location of release (inside AHU just after filters, inside foyers, at return air grille, inside elevator shafts or stairwells, at outdoor air intake vents), type of release and duration (gradual, sudden burst), magnitude or strength, and relative probability of occurrence. Some suggestions of how to frame such scenarios are available. Kowalski et al. (2003) suggest five such attack scenarios where the worst case involves covert gradual release of a CBW agent in the supply duct downstream of the filters. Further, Kowalski (2002) suggests that the standard magnitude and strength of CBR release against which various mitigation measures be evaluated (such as higher filter efficiency or using an UVGI system) be such that 99% of all occupants in the building would die as a consequence. Kowalski’s rationale of such a scenario, which may be deemed rather extreme, is that this definition
provides a convenient way of expressing the performance of countermeasures in terms of the percentage of occupants protected. However, there are no generally accepted consensus guidelines to date of how to formulate a standard set of such CBR attack scenarios for the purpose of assessing relative risk of building occupants to extreme IAQ threats. The problem is by no means simple since the most serious scenarios are unique and one-of-a-kind and cannot be identified a priori from past incidents (as noted by Bukowski [2006] in the context of fire hazard and assessment). Hence, defining a “standard” set of reference attack scenarios on which a relative risk assessment or a hazard assessment is performed seems to be most appropriate.

3. System behavior prediction would involve determining the system’s dynamic response under the conditions stipulated in the previous modules. This would be independent of the CBR agent and focus only on the forced and free dynamic response of the building and the HVAC system. The various alternatives proposed in the published literature are reviewed in the next section;

4. Computing the impacts would entail ascertaining how many occupants are likely to be affected and to what degree (e.g., number of occupants who become sick or die) as well as how it would affect the operation of the building after the event (building cleanup, days of lost productivity). Since this would depend on the CBR agent, there is a need to define a small set of “reference” agents of each type and deduce their corresponding impacts. While the heuristic approach would provide this information directly, the engineering approach applied to our case would entail

• determining the inhaled dose of the occupants in each zone for different time periods (for example, for toxic chemicals one could adopt the five time scales selected by the EPA-AEGL program described earlier);
• using the specific dose-response curves for the particular CBR agent to compute the number of people affected and the severity level (again, the three EPA-AEGL levels could be adopted); and
• computing non-occupant-related monetary implications (mitigation costs, lost productivity, fines).

5. Determining the consequences, or what it means to the owner (in monetary terms) or to the government (in societal terms), is difficult since both occupant and non-occupant factors have to be considered as well as the level to which the occupants are affected. The simpler heuristic weighting scheme, such as that employed in CBT (2004), is appealing but can be faulted on its simplicity. Alternatively, one could adopt a simple multi-criteria consequence or objective function that assigns linear weights to the impacts determined in the previous stage, but assigning such relative weights is highly contentious and imprecise. Even more dubious is the use of a linear model in the first place. For example, the consequences may be the same whether half of the occupants died or even a small fraction; so a nonlinear or even a discontinuous objective function may be more realistic. Despite its obvious difficulty, this is an issue where some heuristic consensus also needs to be reached.

6. Once the consequences of an adverse event are quantified, one would like to evaluate various mitigation measures that can partially or wholly alleviate or reduce the consequence. This would involve defining various mitigation scenarios, such as those related to the HVAC system, as well as those involving management decisions. Alarming systems or continuous monitoring systems would also fall in this category. Note that several iterations are needed to evaluate the consequence of different mitigation measures (link between modules 5–3) under one specified threat scenario, but that several different types of threat scenarios need to be considered as well (link between modules 5–2);

7. Making a final decision would involve studying the numerous evaluations of the consequence function along with their associated costs and perhaps making a decision based on the life-cycle costs (such as the cost-based decision-making software program by Chapman and Leng [2004]). The absolute probability of occurrence of the various threat scenarios also needs to be considered in the decision.
The term “risk-based” assessment has different connotations for different professionals, but a consensus is that it is related to the chance or possibility that an adverse occurrence could happen (Reddy and Fierko 2004). In the most general sense, we can distinguish three separate issues: (a) the identification of hazards or adverse events and their probabilities of occurrence, (b) the consequences of (a) on occupant health, property/equipment damage, cleanup costs, and loss of building operation, and (c) the identification of likely mitigation and disaster preparedness measures to be adopted.

The above three issues can be treated in a deterministic manner, i.e., predict effect assuming that the inputs to the above three issues are specified without uncertainty. This is what seems to be done by most IAQ risk assessment studies to date. A more sophisticated level of analysis would involve explicit consideration of stochasticity (i.e., random variation of parameters and/or effects of assuming guess-estimating parameters that are not measured) surrounding the above issues and studying their ramifications. As much as it is subject to great uncertainty, other ingredients or sources of uncertainty that can provide more insights to the analysis can be identified:

a. **Uncertainty in the probability of occurrence of an extreme IAQ event**: historic data do not allow long-term absolute probabilities to be computed—one simply assigns a value based on heuristic insights from knowledgeable professionals. Introducing an uncertainty distribution around these probabilities can indicate the events that are more serious (and, hence, need better study) as against those that are not.

b. **Uncertainty in framing the boundary conditions**: ability to accurately formulate the forcing functions and the boundary conditions of the extraneous conditions (such as weather) and of the CBR extreme event scenarios.

c. **Uncertainty in the input parameter specifications**, such as the supply airflow rate or the filter efficiency and the occupant density in various zones.

d. **Accuracy of the system behavior prediction** to the base case and to the impact of different mitigation measures (even a multizone simulation model will have some measure of inaccuracy due to model simplification).

e. **Calibration accuracy** of the simulation program or the accuracy with which the model constructed faithfully represents the actual building being studied.

f. **Accuracy of the dose-response relationship** for the particular CBR agent, which will greatly influence the impact function (occupant inter-zonal movement will also have an impact). The uncertainty of this effect is generally much larger than all other uncertainties, except perhaps (a).

g. **Validity of the consequence function** to the owner (both the functional formulation and the weights of the different outcomes).

h. **Cost uncertainty** associated with implementing the necessary mitigation measures identified.

### MECHANISTIC APPROACHES FOR DYNAMIC RESPONSE MODELING

The dose $D$ is the cumulative amount of a CBR agent to which the human body is subjected, while the response $R$ is the measurable physiological change produced by the agent. The widely accepted approach for quantifying dose is to assume the following functional forms based on first-order kinetics:

- **For biological and radiological agents**, where the process of harm being done is cumulative, one can use Haber’s law (Heinsohn and Cimbala 2003):

  $$D(t) = k \int_{t_1}^{t_2} C(\tau) d\tau$$

  where $C(\tau)$ is the indoor concentration at a given time $\tau$, $k$ is a constant that includes effects such as the occupant breathing rate and the absorption efficiency of the agent or species, and $t_1$ and $t_2$ are the start and end times. This relationship is often used to determine health-related exposure guidelines for toxic substances.

- **For chemical agents and for agents in general with acute, dose-rate-dependent effects**, the nonlinear toxic load equation (a nonlinear extension of Haber’s Law) is more appropriate:

  $$D(t) = k \int_{t_1}^{t_2} C^n(\tau) d\tau$$

  where the exponent $n$ depends on the agent or species.

Thus, the dose depends on the time-variant behavior of the indoor concentration, shown as the dynamic system response under Module 3 of Figure 1. One can distinguish between four mechanistic approaches that allow determining this dynamic response using mathematical methods (as against heuristic):

- **CFD models** (for example, Soni [2005] or CBRSim [2005]) give accurate predictions of the spatial concentration distribution of the room provided the boundary conditions are well defined and the model parameters are well calibrated. The latter requires considerable time and expense (and even then can only yield calibration within the accuracy of the airflow measurements), which are compounded by the various standard scenarios that need to be considered. Further, developing a simulation model for a whole building, which captures the various infiltration/exfiltration interactions as well as those of the HVAC and the building, requires considerable effort and can be justified only in critical buildings.

- **Multizone models** such as CONTAM (Walton and Dols 2005) or COMIS (Feustel 1999) are based on the
assumption that the building behaves as a set of well-mixed zones with interzonal flows. They provide information about the dynamic behavior of room average indoor concentrations at a considerable reduction in computational effort as compared to the 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. These models have been used extensively for building-related analysis involving both design and performance evaluation (for example, Musser and Persily [2002]) as well as for assessing the casualty impact from biological agents (Kowalski et al. 2003). Even then, the efforts involved in modeling the building and then calibrating it against monitored data are time consuming, with the latter aspect still an area of active research (for example, Price et al. [2004] and Firrantello et al. [2005]).

Spreadsheet programs involve reducing the number of zones in a building to a small number of aggregated well-mixed zones. Such a representation may be adequate for assessing the vulnerability of building occupants to inhaled dose (Kowalski 2002). 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, while parametric and sensitivity analysis can be performed in a straightforward manner. Though it may be simplistic in certain cases, this path may be attractive and within the competence of many building professionals.

The last option is the use of closed form solutions, which can be obtained for a number of practical one-zone and two-zone building scenarios by adopting a formulation called “compartmental modeling” wherein a large body of knowledge exists. Godfrey (1983) defines a compartmental system as consisting “of a finite number of homogeneous well-mixed, lumped subsystems, called compartments, which exchange with each 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).” Other than computational simplicity, closed form solutions to this set of first-order ODE also allow convenient model parameterization, which is very useful for model calibration using field data, allows uncertainty analysis to be performed easily, and provides insights into which physical parameters need to be measured with more accuracy. The next section further elaborates on this approach.

Other intermediary approaches have also been proposed in the literature:

- zonal models, which provide more refined spatial detail than do multizone models such as CONTAM (Mora et al. 2003);
- a combination of multizone models with CFD models to reduce computational times of the latter (Yuan and Srebiec 2002);
- coarse-grid CFD models, also with the intent of reducing computation times (Mora et al. 2003).

ROLE OF SIMPLE ONE-ZONE MODELS

Consider the one-zone building (or compartment) shown in Figure 2. The supply, return, recycled, and outdoor air intake locations are indicated along with the location of two air filters with efficiencies $F_1$ and $F_2$ (which could be mechanical or chemical filters). Since, usually, many buildings are slightly pressurized, only an exhaust (or exfiltration) airstream is indicated with no infiltration path (it is simple to add this path if appropriate). Two of the most obvious locations for CBR attacks are also indicated as $S_0$ (at the outdoor air intake dampers) and $S_1$ (inside the space). Further, we will assume that the pollutants are nonreactive with air or building materials and do not decay or plate out (though these interactions could be included in the same framework by suitably modifying the model equations). Note that though the density of air varies by more than 10% from 0°C to 20°C, volumetric balances instead of mass balances are commonly used since measurements of

![Figure 2](image_url)
Case study application

The validity of the one-zone analytical treatment is demonstrated by means of a case study building that has been modeled using CONTAM software (Walton and Dols 2005) as described by Firrantello et al. (2006). The building is a dorm building, three stories high, with a total floor area of 17,000 ft² (1579 m²) of which 92% is conditioned by mechanical ventilation from a single air-handler unit (AHU). The whole building has been modeled as 64 zones, of which 7 zones are unconditioned areas (stairwells and elevator shafts), while the remaining 57 zones of conditioned area include dorm rooms, foyers, restrooms, and hallway/corridors. Numerical values of the whole-building basic parameters are shown in Table 2. An attack scenario involving the release of $3 \times 10^8$ cfu/min of an infectious microorganism for 2 minutes at the outdoor air intake is simulated using CONTAM. Figure 3 depicts the concentration levels in each of the 57 occupied zones at three different times from the start of the release (10 minutes, 30
It is clear that except for 5–6 zones (which closer scrutiny revealed to be restrooms and foyer spaces), one can treat the whole occupied space as a single zone. However, the coefficient of variation characterizing the interzone variability does increase with time (1.65%, 9.95%, and 75.7% for the 10-minute, 30-minute, and 60-minute time periods, respectively). Much of the variability, especially at 60 minutes, is due to six zones only as stated earlier. Let us neglect the interzonal variability and compare the dynamic mean response of the system as predicted by the CONTAM simulation against that predicted by the analytical one-zone model (Equations 5 and 6). Such a comparison is provided by Figure 4, where the inset figure is simply one in which the exponential behavior is converted to a linear variation by a log transform for clearer illustration. It is striking that the analytical solution fits the simulated data very closely, with the peak zone concentration deviating only slightly. Note that no parameter estimation has been done; the stipulated overall building parameters used in the CONTAM simulation have also been assumed for the model. In real applications, these parameters will only be known to a certain level of accuracy. This, however, is not a major issue since the parameter estimation can be easily done by linear regression with a log transform.

Figures 5 and 6 also illustrate that the CONTAM simulations are accurately captured by the one-zone analytical model for the cases of a 10-minute release and when the filter efficiency is reduced to 45% (since filters in the field are notorious for being installed badly, or torn, or having large air bypass leakages). Hence, such alternatives are easily studied with the analytical model approach. Further, the combination of the model parameters $a$ and $b$ allow us to study various physical parameters as a group and permit more informed decisions to be made as a result. Finally, one can perform sensitivity analysis in order to determine which factors are likely to have a dominant effect on the overall decision process (higher level perspective) or how the various factor uncertainties impact dynamic response (lower level perspective). A simple manner of assessing the impact of individual physical parameters on these model coefficients is to use the standard formula of error propagation. For example, if one assumes a normal error distribution of 10% CV in each of the physical parameters, the model parameters are affected differently:

![Table 2](image)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V$</td>
<td>Volume of ventilated space</td>
<td>153,150 ft³ (4337 m³)</td>
</tr>
<tr>
<td>$Q_s$</td>
<td>Supply airflow rate</td>
<td>17,140 cfm (8088 L/s)</td>
</tr>
<tr>
<td>$Q_o$</td>
<td>Outdoor airflow rate</td>
<td>2632 cfm (1242 L/s)</td>
</tr>
<tr>
<td>$F_1$</td>
<td>Filter efficiency</td>
<td>0.94</td>
</tr>
<tr>
<td>$S_o$</td>
<td>Contaminant injection rate</td>
<td>$3 \times 10^8$ cfu/min</td>
</tr>
</tbody>
</table>

![Figure 3](image) Contaminant concentration levels in various mechanically ventilated zones of the dormitory building (foyer, hallway/corridors, restrooms, and dorm rooms) assuming one air handler and two-minute sudden release downstream of the air handler: (a) after 10 minutes from start of release, (b) after 30 minutes from start of release, (c) after 60 minutes from start of release.
\[ a = 0.017186 \pm 11.7\% \]

\[ b = 117.53 \pm 130\% \]

Hence, the combined impact of the uncertainties of the physical parameters are much more important on the uncertainty of model parameter \( b \) than that of \( a \). Further, sensitivity analysis provides an indication of the contribution of each individual physical variable on \( a \) and \( b \), as can be gleaned from a tornado diagram depicting one-way sensitivities (Figure 7). It is clear that the high uncertainty in \( b \) arises from that of filter efficiency \( F_2 \), and the only way to reduce the uncertainty in \( b \) is to reduce that of \( F_2 \). It is analyses such as these that are simple to perform using analytical models that provide insights into which physical parameters need more careful measurements, thereby allowing experimental resources to be allocated accordingly.

**CONCLUDING REMARKS**

The basic premise in studies related to assessing building vulnerability is that there are criteria toward which we can strive, although this may not be true or feasible. The current thinking among fire hazard assessment professionals is that since the data needs for the risk evaluation model are unlikely to be known with confidence, it is better to adopt a relative risk approach rather than an absolute one (Bukowski 2006). We make an attempt, in this paper, to provide a conceptual framework by which building professionals can view the issue of assessing the vulnerability of an existing building to extreme events in terms of a probabilistic, relative risk-based decision methodology and to identify cost-effective measures for reducing the threat. We point out that several aspects of the methodology require a consensus approach in their formulation (which can be refined over time), while others can be addressed in a scientific/technical manner. Breaking up the whole problem in this manner would allow, not only better appreciation of the various individual elements completed to date and an understanding of where and how they fit together, but equally allow better synthesis of completed and ongoing research and indicate where resources should be placed in terms of future research and development. The ultimate result could parallel the path taken by the fire regulation community, which is moving toward the replacement of prescriptive codes with performance codes and trying to develop a “harmonized method of analysis acceptable in most countries” (Bukowski 2006).

**ACKNOWLEDGMENTS**

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**ACRONYMS**

ACGIH  American Conference of Governmental and Industrial Hygienists

AEGL  Acute Exposure Guideline Levels (by EPA)
**Figure 5**  Same as Figure 4 but for the 10-minute release duration scenario.

**Figure 6**  Same as Figure 4 but with filter efficiency reduced from 0.94 to 0.45.
**Figure 7** Tornado diagrams indicating one-way sensitivity results of model parameters a and b due to uncertainty in the basic variables. A normal distribution with 10% standard deviation has been assumed for all basic variables. The numbers shown against each basic variable are the numerical values of the corresponding sensitivity coefficients. (a) For model parameter a; (b) for model parameter b.

<table>
<thead>
<tr>
<th>NOMENCLATURE</th>
</tr>
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<tbody>
<tr>
<td>ACH = air changes per hour</td>
</tr>
<tr>
<td>C = concentration</td>
</tr>
<tr>
<td>F1, F2 = efficiencies of filters 1 and 2</td>
</tr>
<tr>
<td>Q = airflow rate</td>
</tr>
<tr>
<td>S = magnitude of CBR release or injection rate</td>
</tr>
<tr>
<td>t = time</td>
</tr>
<tr>
<td>t1, t2 = start and end times</td>
</tr>
<tr>
<td>V = volume of zone</td>
</tr>
<tr>
<td>x, y, z = Cartesian coordinates</td>
</tr>
<tr>
<td>&lt;C&gt; = average concentration</td>
</tr>
<tr>
<td>σ = standard deviation</td>
</tr>
<tr>
<td>τ1 = duration of CBR release</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subscripts</th>
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</thead>
<tbody>
<tr>
<td>e = exfiltration</td>
</tr>
<tr>
<td>m = mixed</td>
</tr>
<tr>
<td>o = outdoor</td>
</tr>
<tr>
<td>r = recycle</td>
</tr>
<tr>
<td>ret = return</td>
</tr>
<tr>
<td>s = supply</td>
</tr>
<tr>
<td>1,2 = zone numbers</td>
</tr>
</tbody>
</table>

**REFERENCES**

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APPENDIX A
EXISTING SOFTWARE TOOLS

Some of the better known software tools related to risk assessment and mitigation measures in buildings are briefly described below.

RAMPART, developed by Sandia National Laboratory (Hunter 2001), specifically analyzes risks arising from natural disasters for General Services Administration (GSA) buildings. It allows assessing risks due to terrorism, natural disaster, and crime in federal buildings nationwide by drawing on a database of historic risks for different disasters in different regions in the US. It can also be adapted to other types of critical facilities, such as embassies, school systems, and large municipalities.

Cost-Effectiveness Tool, developed by NIST (Chapman and Leng 2004), allows an economic evaluation of alternative risk mitigation strategies and, for implementation, is meant to aid facility owners and building managers in selecting cost-effective strategies as a result of natural and man-made hazards. Though the economic evaluation methodology is sophisticated, the user has to supply the risks and the types of mitigation measures and their associated costs.

Building Protection Toolkit (BPTK), developed by the Naval Surface Warfare Center (reference IBTK 2005), is an engineering software meant to model the effects of CBR agents and to assess protective strategies and tactical responses. The software consists of four tools: (i) CONTAM, for calculating internal transport of CBR material; (ii) MESO/RUSTIC, for calculating external transport of CBR in urban environments; (iii) ACATS, an interactive real-time simulation of CBR events for training responders; and (iv) IBTK for evaluating the costs and benefits associated with CBR protective technologies.

BVAMP (2005), developed by LBNL, assesses building vulnerability to CBR attacks based on questionnaire responses and recommends simple measures that building owners can take specific to their building. 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.).

Chemical/Biological Building Protection Tool (CBT), developed by UTRC (CBT 2004), is meant as a screening tool to evaluate overall vulnerability of a particular building or facility in terms of physical (IAQ, etc.) threats and to reach decisions involving engineering alternatives, management practices, and financial mechanisms. It is also based on questionnaire responses provided by the user. For example, 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). However, it relies on pre-calculated 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.

CBR Simulation Tool (CBRSim 2005), developed by the Engineering and Research and Development Center (ERDC) of the US Army Corps of Engineers, is a set of tools for modeling and simulating infiltration of contaminants into individual buildings when CBR agents are released over a facility or installation that is spread over a geographic area. It includes puff models to simulate transport of externally released modes (air drop weaponized agents, industrial accidents, aerial spray, etc.) and a CFD model for indoor transport. It incorporates databases of source terms of several weaponized agents and toxic chemicals, and its advanced visual charts of scenario outcomes are especially useful for providing installation planners with a means to make well-informed strategic decisions regarding alternative building designs, better planning of escape routes, and optimum placement of sensors.

APPENDIX B
COMPARTMENTAL MODELS FOR TWO-ZONE BUILDINGS

One AHU and Two Fully Mixed Zones (see Figure B1)

The following contaminant mass balances are formulated: Indoor zone:

\[
\frac{dC_1}{dt} = \frac{Q_{x,1}}{V_1} C_1 - \frac{Q_{x,1}}{V_1} C_1 - \frac{Q_{2-1}}{V_1} C_1 + \frac{Q_{2-1}}{V_1} C_2 + \frac{S_{1,1}}{V_1}
\]  

(B1)
Return air point:
\[ C = \frac{C_1 Q_{ret,1} + C_2 Q_{ret,2}}{Q_{ret,1} + Q_{ret,2}} \] (B2)

Mixed air point:
\[ C_m = C_s = \frac{S_0}{Q_s} (1 - F_2) + \left(1 - \frac{Q_o}{Q_s}\right)(1 - F_1)C \] (B3)

which, after some algebraic manipulation, yields
\[ \frac{dC_1}{dt} = a_{11} C_1 + a_{12} C_2 + b_1 \] (B4)

where
\[ a_{11} = \left\{ \frac{Q_{s,1}}{V_1} \left[ (1 - \frac{Q_o}{Q_s})(1 - F_1) \left( \frac{Q_{ret,1}}{Q_{ret,1} + Q_{ret,2}} - 1 \right) - \frac{Q_{2-1}}{V_1} \right] \right\} \]
\[ a_{12} = \left\{ \frac{Q_{s,2}}{V_1} \left[ (1 - \frac{Q_o}{Q_s})(1 - F_1) \left( \frac{Q_{ret,2}}{Q_{ret,1} + Q_{ret,2}} + 1 \right) \right] + \frac{Q_{s,2}}{V_1} \right\} \]
\[ b_1 = \frac{S_0}{Q_s} \frac{Q_{s,1}}{V_1} (1 - F_2) + \frac{S_{1-1}}{V_1} \] (B5)

Analogous expressions can be deduced for the indoor concentration in the second zone. Matrix notation allows a compact formulation such as the following:
\[ C' = AC + B \] (B6)

or
\[ \begin{bmatrix} \frac{dC_1}{dt} \\ \frac{dC_2}{dt} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \] (B7)

The eigenvalues for such a linear system, which control the dynamic free response of the system (i.e., how the indoor air concentrations vary over time), are given by
\[ \lambda = \frac{1}{2} \left( a_{11} + a_{22} \right) \pm \left( \left( a_{11} - a_{22} \right)^2 + 4a_{12}a_{21} \right)^{1/2} \] (B8)

Closed form solutions are available for several types of cases of interest to CBR events. A pertinent instance of how a uniform CBR release in one zone propagates through the entire building can be predicted.

**Two AHUs and Two Zones (see Figure B2)**

This case can also be expressed in a matrix form such as Equation B6 with the model coefficients given by:
\[ a_{11} = \left\{ \frac{Q_{s,1}}{V_1} \left[ (1 - \frac{Q_o}{Q_{s,1}})(1 - F_{1,1}) - 1 \right] - \frac{Q_{2-1}}{V_1} \right\} \]
\[ a_{12} = \frac{Q_{2-1}}{V_1} \] (B9)
\[ b_1 = \frac{S_{0,1}}{V_1} (1 - F_{2,1}) + \frac{S_{1-1}}{V_1} \]