Protecting Buildings against Airborne Contamination

Daniel Cousins and Steven D. Campbell

For both homeland security and military defense, buildings must be defended against airborne chemical and biological hazards. In considering which types of attacks might occur, it is clear that many different hazardous contaminants and scenarios can be involved. Fortunately, buildings offer many options for contaminant mitigation and exposure reduction. Passive protective measures have been effectively used for years and include architectural features, physical security, and air filtration. Recently emerging air monitoring sensors allow active protective measures that can complement and extend the protection afforded by passive measures. These active measures include HVAC and building mechanical changes, directed use of personnel protective equipment, and directed movement of occupants to safe shelter. Determining the most appropriate integrated protective system is a daunting systems engineering problem. This problem is addressable by using several quantitative figures of merit, as shown by case studies of the Hanscom Lincoln Testbed/Hazardous Environmental Protection System.

» **Consider the following scenario. At 8:30** a.m. on an ordinary day at Central Headquarters facility, a vending machine service technician arrives. He shows his contractor badge to security, opens his toolbox for inspection, and walks though the metal detector. He is waved through and proceeds on his rounds. At his second vending machine cluster, he opens the machine, adjusts the coin mechanism, and casually places a shoebox-sized device behind the machine. He plugs the inconspicuous box into wall power and moves on to the next cluster. Within a half hour he leaves the building. As he drives away he activates the device by placing a cell phone call to its embedded receiver. A small pump begins to whir inside the box and emits a fine mist of antibiotic-resistant *Bacillus anthracis* spores into the hallway. Passersby notice no smell, see nothing in the air, and ignore the faint sound coming from the vending machine cluster. The mist quickly spreads through hallways into the ventilating system and permeates the building. Over the next hour, large numbers of Central Headquarters personnel are infected. Several days later, symptoms appear, many people are hospitalized, the building is closed, and a national security investigation begins. The enemy is nowhere to be found.

This example is a dramatic but plausible illustration of the vulnerability of buildings and their occupants to airborne contaminants. Buildings are at well-known fixed locations and may be found in mixed-use urban areas with little or no restricted perimeter access. Prime candidates for chemical–biological (CB) attack include government headquarters, military facilities, courthouses, national banks, and other financial institutions. Other candidates for attack include assembly buildings (arenas, convention centers), transportation terminals, and mail distribution facilities.

The mechanical heating, ventilating, and air conditioning (HVAC) systems used to supply outside fresh air to occupants are equally efficient at distributing airborne contaminants. Once a contaminant is indoors, the confined nature of this space keeps the contaminant from dispersing and diluting and thereby increases the hazard to occupants. Typical entry screening measures (e.g., metal detectors) are not adequate for detecting the relatively small quantity of contaminant needed to present a substantial hazard. In particular, lethal indoor exposures require only an extremely small quantity of biological materials. Additionally, biological hazards can be covert, in which the contaminant and any release mechanism are inconspicuous or even imperceptible.

Fortunately, buildings also present attractive options for defense. Their infrastructure, if properly utilized, can provide shelter and safety to occupants; they can be physically modified, or hardened, to lessen the magnitude of attack. Modern HVAC systems can be controlled to mitigate exposure in direct response to sensing contaminant. Buildings are also relatively conducive to hosting protective equipment in that they provide power, data communication, and benign environments, and they allow for regular maintenance.

The proper selection of defense options depends on many factors, including the nature of the contaminants involved. There are dozens of traditional biological and chemical warfare agents, as well as hundreds of toxic industrial chemicals and even nontraditional agents [1]. Contaminants differ widely in many properties, such as toxicity, perceptibility, types of symptom produced, ability to be communicable, persistence in the environment, filterability, vapor pressure, specific density, availability, and ease of weaponization. Table 1 presents data on several contaminants to illustrate the wide range of hazardous properties that exist as well as the challenge to defend against each agent. Contaminants can be evaluated as significant threats in specific scenarios by calculating a weighted sum of the various contaminant properties. In this manner, a lower-toxicity material that is widely

Table 1: Contaminant Properties

AGENT	AGENT TYPE	MINIMUM LCT_{50} (mg-min/mm^3)	LETHAL DOSE (mg)	SYMPTOMS
Variola (smallpox)	DNA virus	1.36×10^{-6}	2×10^{-8}	Pustular skin rash, fever
Bacillus anthracis	Bacterial spore	5.30×10^{-4}	1×10^{-5}	Respiratory distress, fever, shock
Botulinum	Neurotoxin	0.08	1×10^{-3}	Flaccid paralysis, respiratory failure
Sarin (GB)	Chemical-warfare nerve agent	100	1	Runny nose, watery eyes, small or pinpoint pupils, eye pain, blurred vision, drooling, sweating, cough, chest tightness, rapid breathing, confusion, weakness, headache, nausea, convulsions
Acrolein	Toxic industrial chemical	8000	100	Irritation of skin, mucus membranes, and respiratory tract; cough; difficulty breathing
Chlorine	Toxic industrial chemical	19,000	300	Cough; difficulty breathing; burning sensation in nose, throat, and eyes; watery eyes; blurred vision; nausea; vomiting; skin irritation

available may be deemed a more significant threat than a higher-toxicity material that is not widely available.

Contaminant toxicity causes lethality by cumulative exposure or dose D, defined as the integrated product of aerosol concentration $C(t)$ over time:

$$D = \int C(t)dt \,.$$

Various standards of dose exist, most notably LCT_n, which denotes the dose for which n percent of a population can be expected to be lethally exposed. The lethality $L(D)$ for a given dose is

$$\begin{aligned} L(D) &= \mathrm{P}(\mathrm{Death}/\mathrm{Dose}) \\ &= \Phi(\log_{10}(D/LCT_{50}) \times \beta) \,, \end{aligned}$$

where Φ is the normal cumulative probability distribution function and β refers to the probit slope. Other standards of dose exist, particularly for sublethal acute exposures and long-term chronic effects of exposure to chemical contaminants. The Acute Exposure Guideline Limit (AEGL) is widely used by the Department of Energy and the Environmental Protection Agency, with AEGL-1 level associated with discomfort, AEGL-2 with irreversible impairment, and AEGL-3 with life-threatening effects. Other toxicity metrics are used, as designated by government agencies: the temporary emergency exposure limit (DOE), imminent danger to health and life (National Institute for Occupational Safety and Health), permissible exposure limit (Occupational Safety and Health Administration), and maximum exposure guideline (U. S. Army Center for Health Promotion and Preventive Medicine).

Even for a particular contaminant, the range of hazardous scenarios is large. A release may originate at an external distant location and rely on winds to transport the contaminant onto the target. The contaminant can be delivered as a nearly instantaneous point-burst release or a more sustained moving-line release, as shown in Figure 1. In both cases, the contaminant transports in the direction of the ambient wind and also disperses because of atmospheric turbulence. The quantity of material that must be released to yield substantial hazard to occupants strongly increases with distance from release location to

Table 1: Contaminant Properties

AGENT	HEALTH EFFECTS	ONSET	PROTECTIVE CHALLENGES
Variola (smallpox)	10–40% lethal	7–17 days	Communicable; ineffective treatment after symptoms appear
Bacillus anthracis	100% lethal if untreated	1–6 days	Environmentally hardy
Botulinum	100% lethal, supportive treatment to prevent disease progression	12–36 hours	Fast-acting bio-agent, large treatment burden for exposed population
Sarin (GB)	Neurological impairment, suffocation, and death	Seconds at high concentration, up to 30 minutes at low concentration	Odorless gas
Acrolein	Pulmonary edema	Seconds at 30 ppm concentration	Poorly filtered
Chlorine	Pulmonary edema in 2–4 hours	Seconds at high concentration	Widely available in large quantities

intended target. As illustrated in the figure, the point-burst release produces a narrow dosage region within which there is a high probability of lethality. By contrast, the moving-line release spreads the agent over a wider area with a lower lethality probability. But even though the probability of lethality is lower in the moving line, the larger area of exposure can result in greater overall number of fatalities for a highly populated region.

For a particular contaminant and release location, the time duration of the release also affects the dose in a specific region. Shorter, more concentrated bursts, shown on the left of Figure 2, may reach a small population with high dose. A longer burst with a lower concentration may initially affect a larger population, but would allow the affected people to leave the region before they receive a lethal dose.

The hazard resulting from a release of a particular quantity of a particular contaminant is also strongly dependent on meteorological conditions. Atmospheric conditions with a stable low-level layer will restrict the upward dispersion of contaminant released at ground level and thus lead to a more intensely concentrated contaminant plume. Such conditions will most likely occur from dusk through dawn because midday solar heating causes a higher degree of atmospheric mixing. Moderate winds will also serve to contain the plume laterally as it transports and will deliver the contaminant efficiently onto a distant target. Materials aerosolized in the 1 to 10 μm range are generally considered to be most hazardous, because of effective long-range transport and deep penetration into the human respiratory tract. Plumes will generally take the shortest path around or above buildings. Rain, fog, or snow will tend to disrupt the transport of aerosol and thus should be considered non-ideal attack conditions.

Another class of hazardous scenarios are indoor releases. Such releases must be acknowledged because entry screening is not fully effective and the threat of an "inside job" always exists. A release could originate from a lightly traveled hallway or unoccupied room, or targeted directly into the building air intakes. The release may be covert through the use of readily available aerosol dis-

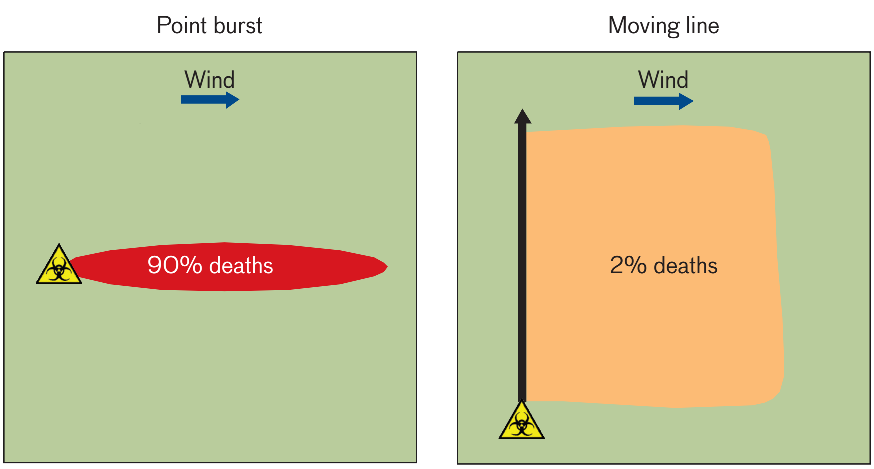

FIGURE 1. Two attack scenarios that rely on wind flow to carry contaminants toward a target. A point burst, shown on the left, covers a small area with a high concentration, while a moving line spreads the contaminant over a large area with a low dosage, shown on the right. It may be easier to avoid the small area concentration, but the high contamination would be highly lethal.

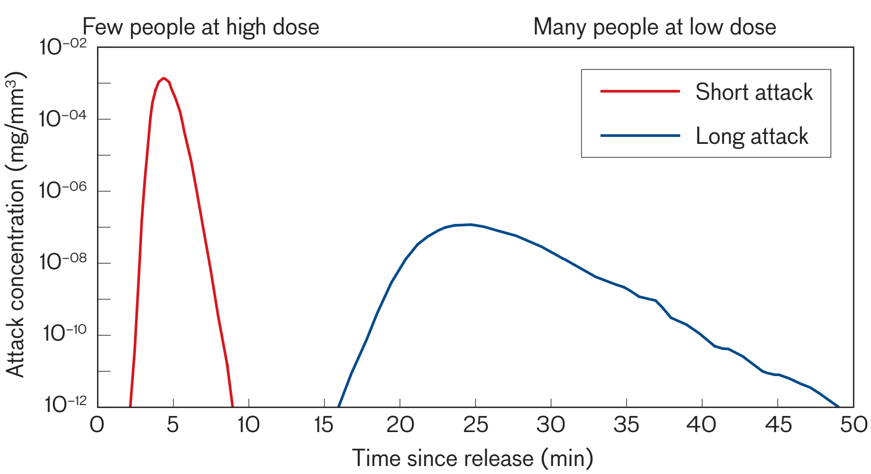

FIGURE 2. Similar to the location concentration effect of Figure 1, the duration and level of an attack have an impact on the total dosage that a victim receives. Faster, higher concentrations may impact fewer people in a location during a specific time period, but their dosage would again be much higher.

seminators, or it could be simply dumped or exploded. The amount of agent released internally that would result in a substantial hazard to occupants is much lower than for an external attack. The 2001 Hart Senate Office building was contaminated with approximately 1 g of *Bacillus anthracis* (*Ba*) spores released by opening an envelope (additional details about this attack are given in the sidebar "Hart Building Anthrax Attack" on page 136). Because the enclosed letter made it apparent that this was an anthrax attack, all of the persons exposed within the building were successfully treated with antibiotics. However, a small fraction of the spores were squeezed from the envelope during processing at a mail facility and further mail handling. Consequently, two employees of the mail processing facility contracted inhalation anthrax and died. More surprising, given the fact that the letters were mailed from New Jersey to Washington, D.C., persons as far away as New York City and Connecticut died of inhalation anthrax apparently because of exposure to a tiny number of spores cross-contaminating other envelopes.

Building Vulnerabilities

Hazardous airborne conditions are calculated by using several aerosol transport modeling tools. External plume formation, transport, and dispersion can be calculated by using LaGrangian (Gaussian puff) and Eulerian (computational fluid dynamics [CFD]) models. In general, there is a trade-off between model complexity and runtime versus results fidelity. The Hazard Prediction and Assessment Capability (Defense Threat Reduction Agency) [2], VLSTRACK (Naval Surface Warfare Center), and CALPUFF (EPA) are commonly used Gaussian puff models. Such models predict the three-dimensional concentration field versus time, accounting for buoyancy, terrain elevation, turbulence, and surface deposition, and they are linked to databases on contaminant properties. They do not account for specific plume realizations, nor do they account for transport through foliage, aerodynamic flow around buildings, or agent interaction with the environment. Such models typically have run times of minutes and are used in a batch post-processing mode to account for the effects of airborne hazards in mission planning. More sophisticated transport and dispersion CFD models, such as FAST3D (Naval Research Laboratory), FEM3MP (Lawrence Livermore National Laboratory [LLNL]), CAMEO (National Oceanic and Atmospheric Administration), QuikPlume [3] (CFD Research Corp), and MESO/RUSTIC (ITT), are used to provide higher-fidelity dynamic effects of specific building and terrain geometry.

Different transport modeling tools can predict indoor transport. Simple differential equation models can be developed to describe the airflow into and out of a single-zone simplified building. A typical single-zone HVAC system and corresponding single-zone model are described in the sidebar "Building HVAC Systems" on page 140. More sophisticated indoor airflow models, such as CONTAMW (National Institute of Standards and Technology) and COMIS [4] (Lawrence Berkeley National Laboratory), predict internal dynamic pressure differences and resulting airflow within zones, assuming instantaneous uniformly mixed zones. The use of such models requires detailed inputs of HVAC configuration, interior partitions, and infiltration paths. Since the actual states of doors, windows, and HVAC components can be difficult to know in practice at a given time, results from such models are challenging to interpret. In addition, the effect of moving building occupants is believed to be significant but is not currently well accounted for in the models.

The Immune Building Toolkit (Defense Advanced Research Projects Agency) [5], an integrated outdoor/indoor transport modeling suite, links various outdoor and indoor models, includes a simple user interface, and provides cost estimation and entity-level models for scenario-based analyses of personnel movements. The Building Vulnerability Assessment and Mitigation Program (LLNL) is another integrated building protection software tool.

We can determine the quantitative vulnerability of buildings by examining the effect of certain hypothetical releases targeted against a specific site, such as Lincoln Laboratory, located on Hanscom Air Force Base. Figure 3 shows the Lincoln Laboratory facility and, in particular, highlights the South Laboratory auditorium, which can be occupied by as many as 350 persons for special events. We have evaluated several release scenarios, such as the case of an outdoor release of 1 kg *Ba* spores from an inconspicuous location about 500 m south of the South Laboratory auditorium. Figure 4 shows the resulting airborne contaminant concentration both outside the

Hart Building Anthrax Attack

A simple mail delivery creates hazardous conditions and significant disruptions.

Sometime shortly before October 9, 2001, envelopes containing approximately 1 g of highly refined *Bacillus anthracis* (*Ba*) spores were sent via U.S. mail to Senators Patrick Leahy and Tom Daschle [a]. At the time, the Capitol had received numerous anthrax hoaxes. Even before these mailings were sent, around September 18, similar envelopes arrived in newsrooms of ABC, NBC, CBS, and the *New York Post* in New York City and American Media in Boca Raton, Florida. These letters contained less highly refined *Ba* material.

The federal government did not immediately comprehend the effect of these media envelopes. Several people were hospitalized before Centers for Disease Control was initially notified on October 3. The Daschle envelope was opened on October 15 on the sixth floor of the building and resulted in the contamination of the Senate Hart Office Building. The Hart Building, shown in Figure A, contains approximately 10 million cubic feet of office space housing fifty senators and their staffs, as well as committee rooms. The envelopes also contained written text that alerted staff to the nature of the attack and immediately prompted emergency measures to be taken. The Leahy letter was initially misplaced, never delivered, and only discovered in November in sequestered mail. Figure B shows the letter.

FIGURE A. The Hart Senate Office Building was the scene of the *Ba* attack on October 9, 2001.

Three thousand workers were tested for *Ba* exposure and thirty-one tested positive. The U.S. Capitol Police, in conjunction with the Environmental Protection Agency (EPA) and several other government agencies, conducted extensive testing of hard, soft, porous and non-porous surfaces throughout the building [b]. Samples taken in the following days confirmed contamination on the first, fifth, and ninth floors, and the HVAC system. As a result, the building was closed on October 17. Tracing of the mail handling path also led to the closure of the Washington, D.C., Processing and Distribution Center in Brentwood, Md., on October 21. Contamination was later detected throughout the Capitol complex, Supreme Court, and Library of Congress.

At the time of the incident, there was no EPA-approved *Ba*

building and inside the auditorium. The dose received by auditorium occupants would exceed lethal levels within several minutes, yet these conditions would be completely imperceptible to occupants.

Another hazardous scenario to consider is shown in Figure 5, the indoor release of 1 liter sarin (GB) nerve agent in the prefunction area just outside the auditorium. Normal interzonal mixing of the air would quickly cause the auditorium occupants to receive a lethal dose. The sarin vapor concentration within the auditorium would peak at 0.28 mg/m^3, and thus the dose would ultimately exceed the 50% lethality level. Unguided evacuation would result in people entering the even more concentrated prefunction area.

Figures of Merit

We can use several figures of merit to evaluate the effectiveness of building protection. They assume specific attack scenarios, building and HVAC configuration, and occupancy models.

remediation process for an entire contaminated building. After consideration of a wide range of remedial alternatives, including unsuccessful trials of other materials, the EPA selected gaseous chlorine dioxide as the primary decontamination agent. Effective procedure was determined to be gaseous chlorine-dioxide exposure for 12 to 48 hrs at 750 ppm, with humidity controlled at 75% and temperature above 70° F. Windows were blacked out to minimize degradation of the chlorine-dioxide gas that occurs when it is exposed to ultraviolet light. Spot treatments including High-Efficiency Particulate Air (HEPA) vacuuming and liquid chlorine dioxide were conducted on small hard surfaces. Over 300 critical items, such as document and personal effects, were taken offsite and sterilized with ethylene-oxide gas before being returned to the building. The toxic nature of chlorine-dioxide gas was rendered safe for release into the atmosphere by chemical reaction with sodium bisulfate.

The standard for reopening the building was to detect no viable *Ba* spores on surrogate sample strips placed throughout the building at a density of 1 per 100 sq ft. Surface sampling was also conducted with dry and wet wipes and vacuum samples. After the EPA confirmed that this standard was met, the Hart Building decontamination was completed by December 17 at a cost of $42 million.

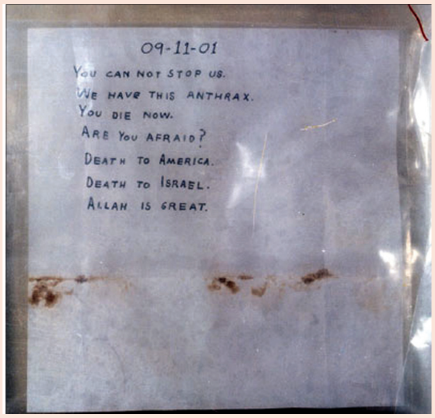
09-11-01
YOU CAN NOT STOP US.
WE HAVE THIS ANTHRAX.
YOU DIE NOW.
ARE YOU AFRAID?
DEATH TO AMERICA.
DEATH TO ISRAEL.
ALLAH IS GREAT.

FIGURE B. **The letter enclosed in the envelope warned Capitol Police of the nature of the threat.**

The massive federal investigation to determine and prosecute the responsible party is ongoing as of March 2007. Interestingly, a research article [c] that was published and made available on the World Wide Web in September 2001 described the hazard that a letter with 1 g or less *Ba* spores presented to office workers and mail handlers. Follow-up testing of the Hart Building *Ba* material has reported it to be of the Ames strain, combined with silica but not aluminum, which provide clues to its origin [d]. Testing of 600 direct-drop mailboxes has identified a single mailbox at 10 Nassau St. in Princeton, N.J., to be the likely mailbox used. In total, the six contaminated letters have been linked with 22 cases of anthrax, 5 deaths, and government costs in excess of $1 billion.

REFERENCES

a. http://en.wikipedia.org/wiki/2001_anthrax_attacks.
b. D.R. Stutz, "The Anthrax Chronicles," *8th Int. Symp. on Protection against Chem and Bio Warfare Agents, Gothenburg, Sweden, 2–4 June 2004*.
c. B. Kournikakis, S.J. Armour, C.A. Boulet, M. Spence, and B. Parson, "Risk Assessment of Anthrax Threat Letters," Defense Research and Development, Ottawa, Can., Technical Report DRES-TR-2001-048, Sept. 2001.
d. C.C. Kelly, "Detecting Environmental Terrorism," *Armed Forces Inst. of Pathology Lett.*, vol. 160, no. 4, Aug./Oct. 2002.

The building protection factor (BPF) is defined as the reduction in dose received by a typical building occupant compared to a person located outside the building. An unprotected building will typically have a BPF of slightly above 1. The BPF would typically assume uniform population occupancy within the building and would not specifically address casualties. Another figure of merit for protective effectiveness that accounts for the casualties is the untreated fatality factor (UFF). It is defined as the ratio of lethality of occupants with protection to the lethality of occupants without protection. While UFF is a compelling measure of protection, it can be difficult to calculate because we must account for each occupant's specific location over time.

Another figure of merit that is occasionally used to denote the overall impact of a release to a building is the fraction of building exposed for a given dose, FBE_n. It is defined as the fraction of building floor space in which dose exceeds threshold, LCT_n, compared to the total building floor space.

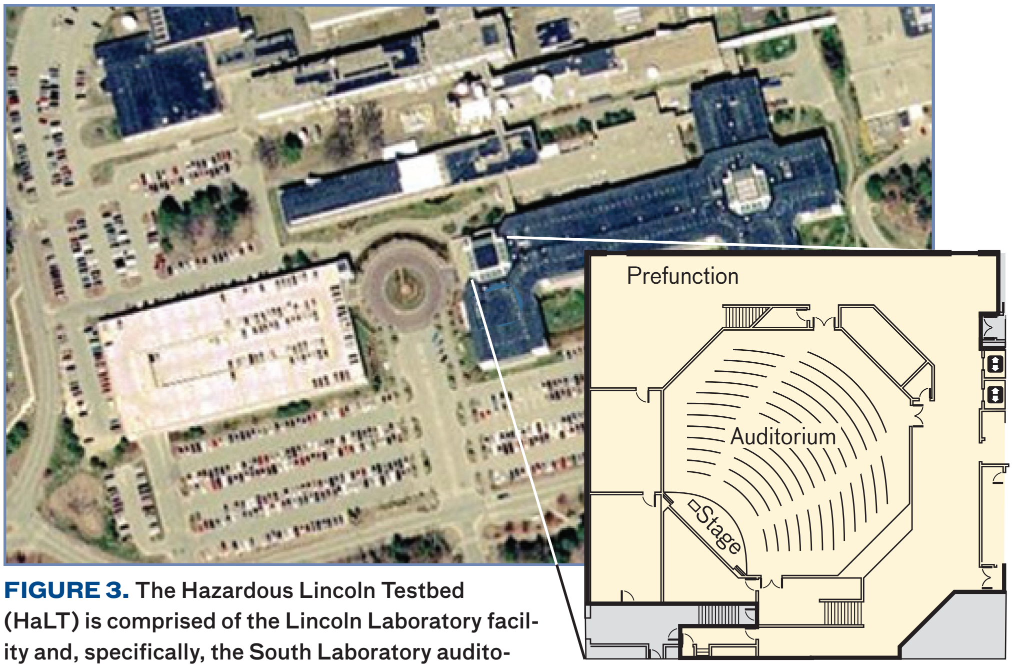

FIGURE 3. The Hazardous Lincoln Testbed (HaLT) is comprised of the Lincoln Laboratory facility and, specifically, the South Laboratory auditorium and prefunction areas.

Another important figure of merit, impact to building operations (IBO), must be balanced against the previous figures of merit. Any protective strategy will have an IBO in terms of added operations and maintenance functions. Disruption of ongoing mission functions may occur with sensor false alarms, depending on the concept of operations. Some actions may be low disruption, such as short-term HVAC changes, while others may be high disruption, such as donning of masks and evacuations. Typically, we may seek to reduce disruptions below some minimum acceptable level. If we are relying on sensors to maintain acceptably low false-positive rates, this attempt requires careful assessment of operating background conditions and perhaps accelerated false-positive testing in lab facilities. We could argue that some low (but nonzero) disruption is actually advantageous because it brings visibility and awareness of the protective actions to occupants, such as occurs during a

0 seconds after release

90 seconds after release

120 seconds after release

14 minutes after release

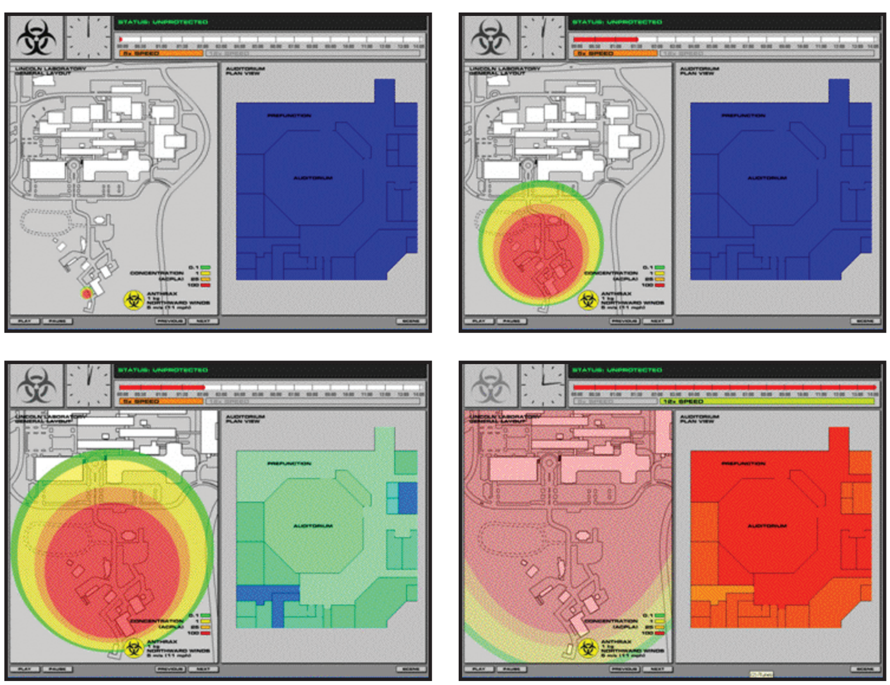

FIGURE 4. Computer-generated data shows the distribution of pathogens in the HaLT region. Here, the focus is on the auditorium and prefunction areas and the concentration levels resulting from 1 kg external *Bacillus anthracis* (*Ba*) attack. Blue indicates safe (<<1 agent containing particles per liter of air [ACPLA]) and red indicates lethal (>500 ACPLA).

fire alarm drill. However, if disruptions are too frequent, then the cry wolf effect will make the building occupants reluctant to cooperate with the required protective actions. To prevent unacceptable facility disruption, the false-alarm rate for high-disruption actions needs to be on the order of months to years. Overall, IBO can be calculated as an incremental cost of building operations, assuming a cost of disruption and a false-alarm rate.

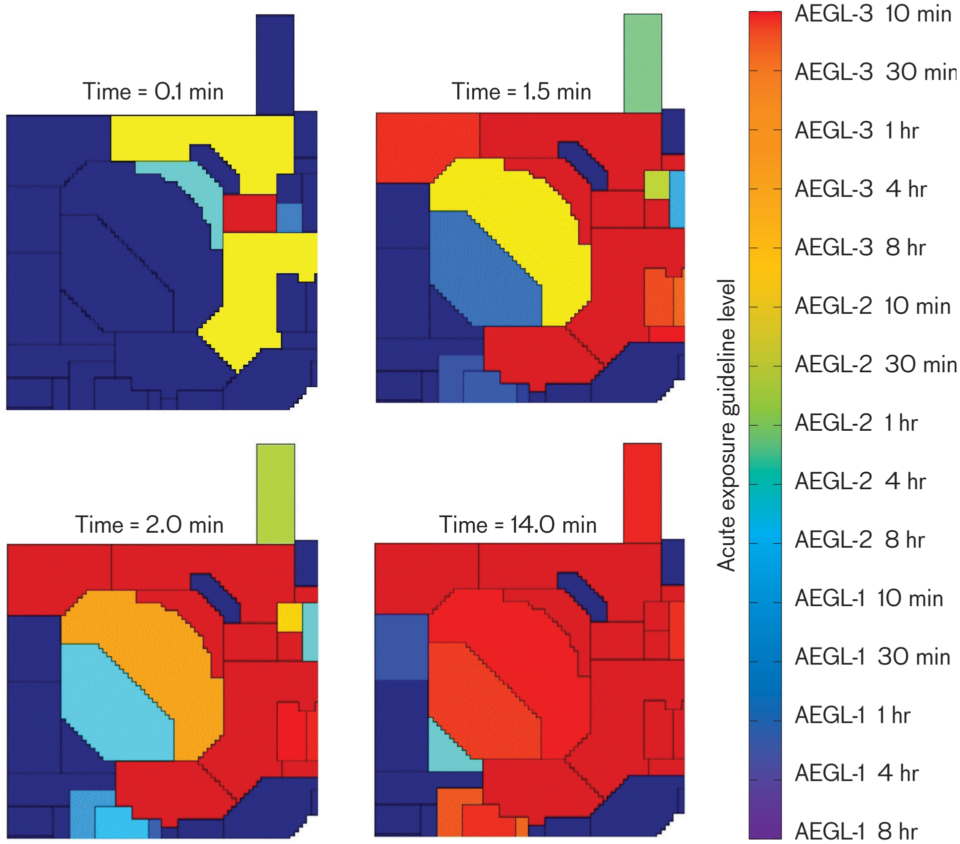

FIGURE 5. The auditorium and prefunction areas show high concentrations of sarin resulting from 1 kg release in the prefunction area. Without any protective measures, the entire prefunction area is contaminated to a lethal dose (acute exposure guideline limit AEGL-3 stages) within two minutes, and the auditorium within fourteen minutes.

Finally, the total life-cycle cost (LCC) of implementing a protective capability must be manageable. Components of LCC are component purchase cost, installation cost, operations cost, and maintenance cost. While it is attractive to seek protective measures with low purchase cost, the installation, operations, and maintenance costs must be acknowledged and controlled. Common sources of installation costs are those related to HVAC mechanical modifications, software upgrades, testing, and accreditation, providing power and data connectivity to sensors and actuators. In general, costs to install by retrofitting existing construction are several times higher than costs of installing similar measures in new construction. Common sources of operations and maintenance are related to labor monitoring and operating equipment, electricity for running higher-capacity HVAC blowers, replacing used filters, laboratory costs for processing samples, and cleaning and recalibrating sensors.

Passive Protective Measures

Traditional building protection has been based on passive measures, such as architectural features, physical security, and air filtration [6–8]. Several architectural features are protective and may be inexpensive, particularly for new construction. Elevating air intakes away from the ground level diminishes some threats because of less proximate access and natural dilution from ground-level releases. Using slanted intake screens provides some protection against contaminant canisters, which could be thrown into air intakes. Isolating zones of personnel and mail entry areas from the rest of the building reduces the effect due to releases originating from these locations.

Active securing and monitoring of indoor HVAC rooms requires physical security measures. Perimeter security involving fences, cameras, and intrusion detection systems will also lessen and deter some threats. Exterior windows may be secured. Although not to be relied on entirely, entry control screening should be used when possible. Because sources of airborne hazards may be associated with pressurized containers, containers of fluids and powders, or altered or missing container labeling, articles with these attributes should be examined carefully. There

Building HVAC Systems

Controlling HVAC system components is critical for rapid response to airborne threats.

Most modern buildings, other than small residences, rely on a mechanical ventilation systems to supply conditioned air to occupants. These systems typically provide conditioned air with heating, cooling, filtering, and humidity control. Building air supply is managed at the zone level, defined by a section of the building served by a single control, and typically a single large air handler. Figure A shows a greatly simplified schematic of an heating, ventilation, and air conditioning (HVAC) zone.

Occupants are provided a mix of fresh outside air mixed with some degree of recirculated air. ASHRAE Standard 62-1999 (Ventilation for Acceptable Indoor Air Quality), the generally accepted standard for commercial buildings in the United States, recommends 15 to 30 cubic feet per minute (cfm) per person of outside air. Occupancy levels range between 7 and 100 persons/1000 sq ft. Depending on the degree of recirculation (80% recirculated, 20% fresh is common), this proportion will result in an overall air exchange rate, commonly at 0.5 air changes per hour. Air is also filtered for particulates to improve air quality and prevent buildup of dust and lint on heating and cooling coils. Medium-efficiency filters—MERV 10 to 12 level, ASHRAE dust spot level of 60% to 80%—are often used. Chemical vapor filtration is rarely used in commercial construction.

In large buildings with heat gains from lighting, occupants, and electronic equipment, interior zones may require year-round cooling, while perimeter zones may require heating or cooling, depending on external conditions. Air exchange between zones is typical, although not well controlled by design. Air exchange within zones depends on the use of above-ceiling plenums, connectivity through hallways, stairwells, elevators, and large open spaces such as atriums. In general, slightly more outdoor air is brought into the building than the exhaust air, and the building is slightly overpressured. Depending on open entries, windows, cracks and wall gaps, and the overpressure differential, inside air will exchange with the outside. Typical exchange levels of 0.1 to 2 cfm/ft^2 will occur at 0.2 inches water gauge (50 Pa) pressure differential. Air can also infiltrate uncontrolled into the building if the forced exhaust exceeds the fresh-air intake, or if strong winds blow against a face of the building. If there is a large temperature differential, air may infiltrate into the ground level.

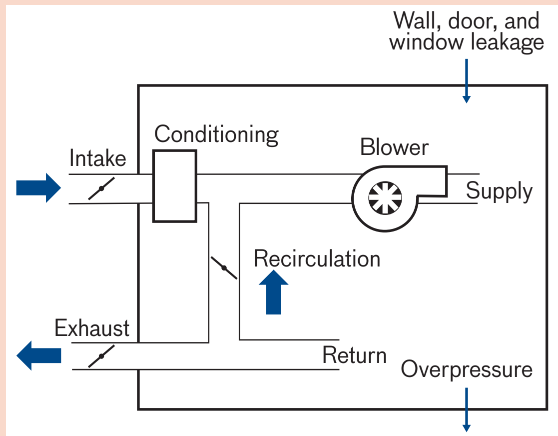

FIGURE A. Each component of the HVAC system, shown here in simplified form, is set in response to specific threat conditions. Adjusting the intake, exhaust, recirculation, and blower controls the primary flow in the building and affect the leakage and overpressure exhaust.

Several different HVAC modes are often used, depending on occupancy and external temperature, commonly a daytime normal mode, a nighttime low-energy consumption mode, and an economizer mode in which heated or cooled air is highly recirculated within the building to conserve energy. Typically, HVAC systems do not switch rapidly between these modes, because of slowly acting dampers and limitations in changing fan speeds quickly. Being able to exploit and rapidly change between HVAC modes is the basis for active building protection.

is no current practical effective technique for characterizing unopened sealed containers and it is unrealistic to fully rely on entry screening to prevent introduction of airborne threats inside buildings.

Conventional particulate filters, in use against airborne hazards since World War I [9, 10], are suitable for capturing biological agent particles, and work by a combination of diffusion, interception, impaction, and removal of particles as a function of particle size [11, 12]. Table 2 lists a range of common particulate filter properties. Note that pressure drop increases with increasing capture rate, although this effect can be offset by choosing larger filters with lower face velocities. Pressure drop also increases with filter age and loading, which ultimately limits filter lifetime. Typical new commercial buildings use minimum-efficiency reporting value (MERV) 8 to 14 filters.

Conventional chemical vapor filters work by molecular adsorption onto the large-surface-area sorbent materials, which can exceed 1000 m^2 of surface area per gram. Capture capacity also depends on residence time, which is determined by filter bed depth and face velocity. Residence time is typically <0.1 sec. Sorbents are effective against a range of chemicals, although some vapors are poorly filtered, such as acrolein. Low-cost sorbents are zeolite, alumina, and activated carbon. A higher-cost higher-performance military standard (MilStd) is ASZM-TEDA carbon, which is suitable for a wider range of chemicals. With continuous use, sorbent sites become depleted and eventually the filter must be replaced to avoid filter breakthrough. Depending on background air vapor levels, chemical filter lifetimes range from a few months to a few years: filters should be replaced on a regular maintenance schedule or by article testing of test cartridges, if available.

In general, upgrading filters from commercial grade to high-efficiency results more elaborate and expensive mechanical blowers and higher energy costs, due to the increased pressure drop that must be supported. Since a small degree of infiltration resulting from duct leakage or filter bypass due to improper installation can compromise high-efficiency filter elements, better filters also require higher level of workmanship and refurbishment of ductwork. High-efficiency particulate air (HEPA) filters should be preceded with low-efficiency dust filters to preserve HEPA lifetime. The current MilStd Class 1 collective protection provides for HEPA particle and carbon filtration, with overpressurization effective against 25 mph winds. Filter costs are typically \$5 to \$10/cfm or \$50 to \$100/ ft^2. For a 100,000 ft^2 building, this translates to \$500K filter purchase cost and \$50K/year operating energy cost.

Recently advanced filtration technology captures (or neutralizes) contaminants with little or no pressure drop. Such technologies allow for effective high-grade filtration without the need for upgrading HVAC blowers. These technologies use energy and/or chemicals to kill biological agents and dissociate chemicals. They can be

Table 2: Particulate Filter Properties

	MERV3*	MERV8	MERV11	MERV14	HEPA*	ULPA*
Application	Prefilter	Low	Commercial Middle	High	Hospital/Cleanroom	
Capture	25%	40%	60%	90%	99.97%	$>10^5$ reduction
Particle size [µm]	>10	3–10	1–3	1	0.3 µm	0.1
ΔP [iwg]	0.1	0.25	0.4–0.7	0.7–1.2	1–3	1–3
Face velocity [fpm]	500	500	500	500	250	200
Cost [2 ft × 2 ft]	\$10–20	\$30	\$40	\$50	\$250–500	Application specific

* MERV stands for minimum-efficiency reporting value, HEPA is a high-efficiency particulate air filter, and ULPA is an ultralow penetration air filter; iwg is inches water gauge, a standard HEPA unit for pressure, and fpm is feet per minute.

used continuously or may be triggered by sensors. Many such technologies are being investigated, including ultraviolet (UV) radiation, pulsed white-light radiation, microwave radiation, electron beam, and photo- or UV-induced catalytic oxidation.

Neutralization effectiveness differs for the various technologies. Low-power germicidal UV has been used in medical settings for quite some time. Several mW/cm^2 of germicidal UV has been shown to achieve one to two orders of magnitude reduction of biologically active material. Recently, commercial systems have demonstrated a high-power UV technology capable of $>10^6$ neutralization of spores that use energy of order W/cfm with exposures <1 sec. In-duct engineered systems suitable for 3500 to 100,000 cfm are available—one such system is the Advanced UV System (AUVS) from Novatron, Inc. Some limitations of neutralization measures are the performance against chemical vapors and the potential for generating toxic byproducts, such as ozone, when the equipment is operated continuously.

Traditional passive measures that have been employed provide reasonable protection against modest levels of externally released agents. However, they provide only marginal protection against massive outside releases, against most indoor releases, and against certain poorly filtered chemical agents. In addition, passive filtration provides no situational awareness of an attack and has no ability to initiate medical treatment.

Active Protective Measures

More recently, buildings have adopted detect-to-treat protective strategies for biological hazards, involving continuous air sampling and periodic sample testing. (Detect to treat is not used for protection against chemical hazards, because the window of effective treatment for chemical agents is generally too short to be practical.) The simplest approach for biological protection is to employ dry filter units (DFUs), which draw large amounts of air through filters to capture airborne biological materials. The filters are then periodically collected and transported to a central laboratory for agent identification and confirmatory testing. While a full discussion of biological identification testing is beyond the scope of this article, typical testing is via sequential combinations of immunological, genetic, and culture tests. The more frequently filters are collected and tested, the sooner medical treatment can begin [13]. False-positive and inconclusive test results do occur, which can result in more time-consuming follow-up testing to resolve and thus further delay treatment. Treatment delay will result in degraded treatment efficacy, which, for antibiotic treatment of *Ba* exposure, may lead to about 10% mortality increase for each day delay beyond day 1. A main limitation of detect-to-treat strategies is the LCC associated with frequent sample processing.

Recently, the development of effective, near real-time biological and chemical agent sensors allows new and highly effective active protective measures [14]. Automatically modifying a building's HVAC and its state in response to sensors enables the building to assume a temporary protective posture. The ideal building protective sensor would detect all contaminants at sublethal concentrations nearly instantly; never miss a detection and rarely make false-positive detection; identify and confirm the type of contaminant; be inexpensive to buy and install throughout the building; be easy to operate and maintain; and require few (if any) consumables.

Although currently there is no such sensor with all these properties, sensors do exist that can provide some of these properties. Highlights of the technology include inexpensive, moderately sensitive remote and point-trigger sensors and rapid identifiers that are extremely sensitive, operate in a few minutes, and have very low false-positive rates.

These sensor types can be exploited in a tiered sensing and protective strategy employing trigger sensors to cover wide areas quickly with follow-up targeted application of slower identification sensors. Protective actions can be taken at various time scales, but because of the high false-positive rates, trigger sensors support only low-disruption actions. Follow-up higher-disruption protective actions would be taken only on the basis of true-positive identification. Equally importantly, disruption is controlled by quickly resuming normal building activities on the basis of true-negative identification. Table 3 lists some available sensors that apply to the following applications. Outdoor trigger-sensor developments that are enabling this approach are particulate lidars and infrared spectroscopic sensors. Indoor triggering can be based on low-cost particulate point sensors. Rapid-identifier sensor developments include rapid-immunological, advanced-optical techniques, and automated gas chromatograph/mass spectrometry. Of particular importance to building protection, sensors must operate in an indoor-air background, which may be cluttered with airborne interferents. Indoor air quality, with attention to sensor interferents, is discussed in the sidebar "Indoor Air Quality."

Another technology enabling active protective measures is the digital data networks typically employed in modern buildings. Most office buildings support a network dedicated to building control and energy management (BCEM) for monitoring and controlling such functions as lighting, HVAC, utilities, and security. A related but separate network is the Life-Safety network, which hosts smoke and fire-alarm sensors, sprinklers, fire doors, and emergency lighting. Life-Safety networks must comply with strict regulations calling for hardened dedicated lines, redundancy, and backup power. The network most apparent to building occupants is the Office Automation network, which supports, for example, emails and web services. These networks differ in both their communications protocols and their physical layer. BACNet is an ASHRAE standard that many BCEM networks follow. LonWorks is a commercial low-bandwidth communications protocol designed to permit open interchangeable architecture among BCEM networks. The physical network layer can involve mixtures of coaxial cables, twisted-pair wiring, and optical fiber. Concerns about security and reliability have so far limited the use of wireless data networking for building control. In implementing active building protection measures, one will typically tie together the various physical layers with various levels of data encryption and wiring segregation to comply with accreditation requirements.

HVAC Protective Strategies

Specific protective HVAC strategies can be implemented, depending on the nature of the attack, particularly the source location. A strategy will consist of a sequence of HVAC modes, implemented at selected zones of the building at particular times. Figure 6 shows the basic HVAC modes that can be used to create a protective strategy: Normal, Overpressure, Shutdown, Minimal, and Purge. Overpressure is achieved by increasing intake and decreasing exhaust to establish a positive internal air pressure over external ambient. The overpressure must exceed typical external wind pressure on the order of 5 Pa.

The goal of Shutdown mode is to avoid the intake of external contaminants. In this mode, the intake, recircu-

Table 3: Application-Based Sensor Development

OUTDOOR TRIGGER SENSORS	SOURCE
Raman-Shifted Eyesafe Aerosol Lidar [15]	ITT Inc.
Windtracer [16]	Lockheed Martin Coherent Technologies Inc.
Mobile Chemical Agent Detector [17]	Northrop Grumman Inc.
Chemical Agent Line Sensor [18]	Lincoln Laboratory
INDOOR PARTICULATE POINT SENSORS	**SOURCE**
Biological Agent Sensor and Trigger [19]	Lincoln Laboratory
Air Sentinel [20]	ICX-Mesosystems Inc.
RAPID IDENTIFIER SENSORS	**SOURCE**
Cellular Analysis and Notification of Antigen Risks and Yields (CANARY) [21]	Lincoln Laboratory
Rapid Aerosol Agent Detector [22]	Lincoln Laboratory
Bioaerosol Mass Spectrometry [23]	Lawrence Livermore National Laboratory
DSQ Gas Chromatography–Mass Spectrometry [24]	Thermo Fisher Inc.

Indoor Air Quality

Typical air circulating in a building is already contaminated with many particulates that affect trigger and false-positive rates.

Indoor-air quality has been thoroughly studied from the perspective of health effects to occupants of buildings and residences [a]. Indoor air, depending on location and nearby activities, may contain various pollutants such as asbestos, mold, tobacco smoke, formaldehyde, radon, and carbon monoxide. Indoor-air quality is important for building protection because of its effects on sensors, particularly as it may result in false-positive detections. Total indoor concentrations of respirable sized (1 to 10 μm) particle range from 10 to 1000 ppl. Although many microorganisms have been identified in indoor air, their effect in causing false positives in biological sensors is not well established [b]. Bacteria and fungi are present indoors at <1 ppl, and only small fractions (approximately 1% of bacteria) will culture. Viruses are difficult to measure, and little data exist on their abundance in indoor air. Typical indoor-air particles are organic but nonviable. The ratio of UV fluorescent to total particles can be as high as 80% at 360 nm excitation, and somewhat less at shorter wavelengths.

Biological sensors may be affected by airborne mold, mildew, and fungal particles; fibers from carpeting and clothing; combustion products; proteinaceous animal materials; saliva; shed skin; and dander. Chemical sensors may be affected by airborne organophosphates such as pesticides, volatile organic compounds such as paints and solvents, glycol ethers such as chemical cleansers and floor strippers, and organonitrides such as fuel, oil, and hydraulic vapors.

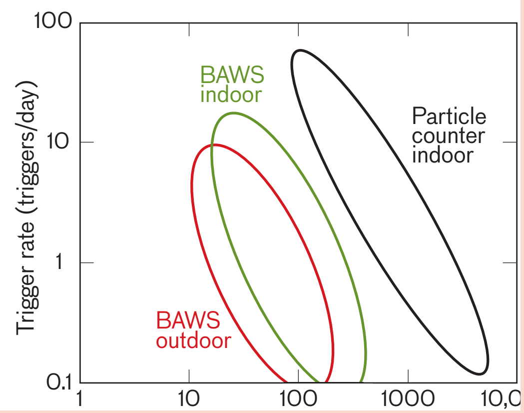

FIGURE A. The relationship between false-trigger rates and detection thresholds is consistent in form for various detectors.

The frequency of false positives depends on specific sensor-model and operating condition, detection algorithm and time, geographic environment, and sampling location. False-positive rate will also be affected by local activities that may generate aerosols or vapors, such as cleaning, construction, machine operations, and HVAC change of state. The same sensor operated in desert, temperate, urban, rural, marine, or littoral environments may differ in false-positive rate by 2 orders of magnitude. Indoor false-positive rates are typically higher than at outdoor sites at a given location. In general, microbial abundance rises with occupancy and activity at a given site, and these factors contribute to increased false-positive rates. Figure A shows examples of biosensor false-trigger rates as a function of detection threshold for various biotrigger sensors with various triggering condition. In general, false-trigger rate can be reduced by using more discriminating phenomena such as particle UV fluorescence, waiting longer to trigger, and excluding triggers that result from nighttime cleaning activities. Comparable data exist for operating chemical sensors indoors, and false alarms may be frequent. Recently, databases are becoming available that permit a systematic evaluation of composition and abundance of potential interferents in various environments.

REFERENCES

a. www.epa.gov/iaq.
b. R. Casegrande, S. Yaeger, M. Csarzar, and T. Myatt, "Microbial Content of Normal Air," Gryphon Scientific, LLC, Technical Report, Aug. 2006.

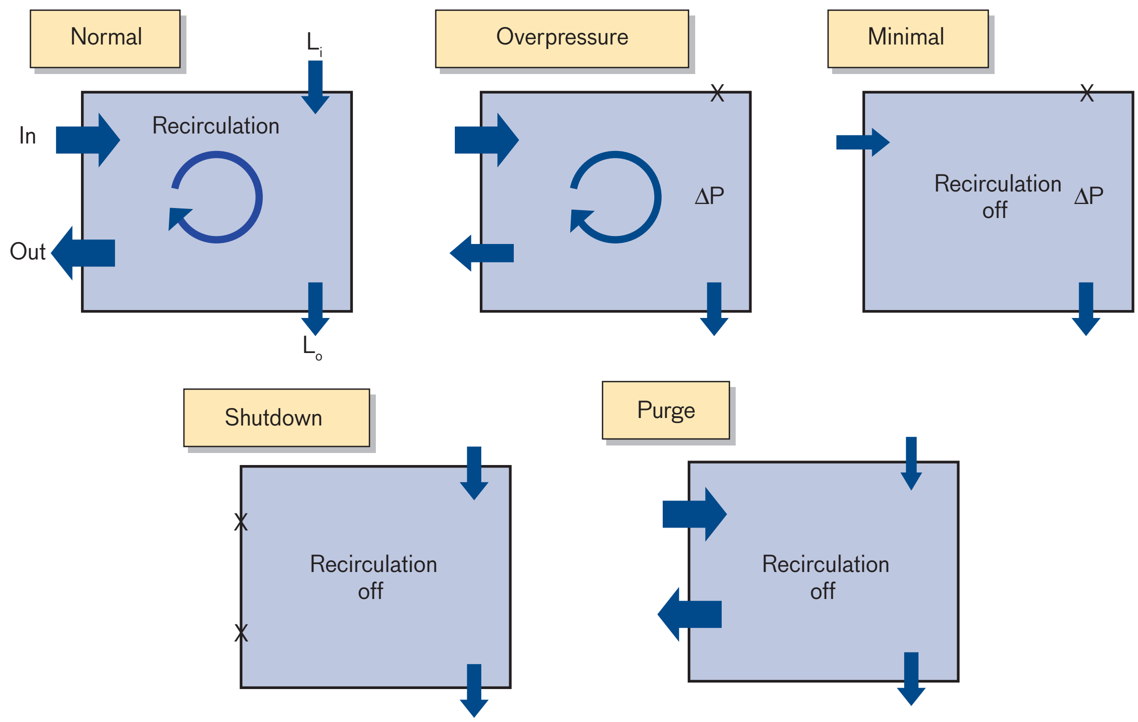

FIGURE 6. The basic HVAC modes listed in Table 4 are shown schematically. The thickness of the arrows indicates the relative magnitude of airflow. ΔP indicates a positive pressure differential relative to the outside of the building.

lation, and exhaust flows are all turned off. The only flows are infiltration and exfiltration, which are equal. However, overpressurization will be rapidly lost and contaminant will gradually infiltrate without passing through filters. To avoid this deleterious effect, one may use the Minimal mode, close the exhaust damper, and reduce fresh-air intake to the minimum amount needed to maintain overpressurization. Since an overpressure is maintained, infiltration is minimal, and contaminants just pass through the intake filter when entering the building.

Finally, in the Purge mode the intake is turned to full fresh air and recirculation is turned off to achieve maximum ventilation of the building. The entire building may be purged once it is certain that an external hazard is no longer present. It is important to purge the building following any contamination because indoor concentrations should be expected to persist long after the outside air intakes are clear. The maximum number of air changes that an HVAC system can achieve in Purge mode is highly variable, but three air changes per hour (ACH) is not unreasonable.

Strategies using sequences of various HVAC modes, depending on the most likely contaminant source location, can be undertaken to provide active building protection systems (BPS) . Table 4 lists the BPF associated with several HVAC filter and control strategies for a simplified single-zone building model.

Despite protective HVAC responses, once contaminant has entered the building, options to consider are evacuation to safety, shelter in place, and use of personal protective equipment (PPE). For an effective evacuation, it must be determined that a greater hazard is not present in the planned evacuation path or end point. Such considerations have recently led to development of dynamic evacuation guidance concepts, which involve real-time sensing and modeling of transport, determination of safe and compromised routes, and communication with building occupants. Note that persons evacuating a highly contaminated area will carry with them some contaminant and thereby further spread the hazard even more with their movement. Shelter in place can also be considered if it is effectively isolated from the contaminant. Smaller restricted-access filtered areas can be established within the building. The integrity of such shelters may require restrictions on personnel access and egress and should be expected to degrade with time after attack. Short-duration escape masks may be useful if they are readily available to occupants. Escape masks, as distinct from full

MilStd PPE gas masks, are compact and do not require special individual fitting. They provide protection during short-duration building evacuation, but do not provide eye protection or filtration of carbon monoxide that may occur during fires. Escape hoods, with a self-contained oxygen supply, do meet these needs at additional cost.

Case Studies of Protective Systems

A building protective system (BPS) consists of a physically integrated system of protective measures together with a concept of operations and trained personnel to support them. The designer of a building protective system has many protective measures to chose from and integrate. In general, we must postulate protective options, construct and exercise models of them, and evaluate the relevant protective figures of merit. We seek a BPS with high BPF and low UFF for a range of credible attack scenarios. At present there are no standards or requirements for these figures. The protective system should have manageable IBO and reasonable LCC. These quantities are not amenable to modeling and can most reliably be determined through installation and evaluation of prototypes.

The specific BPS chosen will depend on the specific building and threat scenarios. Selecting from the wide range of protective measures and integrating them into a protective system is a daunting systems engineering problem. The Hanscom-Lincoln Testbed/Hazardous Environment Protection System (HaLT/HEPS) is being developed at Lincoln Laboratory to create and demonstrate advanced building protection in an operationally representative environment. The specific initial protective capability is being directed to occupants of the South Laboratory auditorium.

HaLT/HEPS has selected an initial set of measures and integrated them into a protective system, as shown in Figures 7 and 8. The HaLT/HEPS sensing method contains real-time trigger sensors, sampling devices, and confirmatory sensors. The biological trigger sensors include the Biological Agent Warning System (BAWS) [25] and a six-channel particle counter; the chemical trigger sensors include the Centurion IMS [26] and an electrochemical sensor for toxic industrial chemicals such as acrolein. The sampling devices are a 96-well-plate dry-particle impactor and a thermal-desorption tube sampler for vapors. Two of the sensor nodes monitor the outside air at the main entrance and roof of the Laboratory; the other two sensor nodes monitor the return air from air handling units serving the auditorium and surrounding prefunction area. A chemical-agent line sensor (CALS) [27] has been set up to remotely monitor an external path for chemical vapors. The sensors from each node are monitored by a command and control system (CCS), which includes a graphical user interface for operations and data archiving capability for testbed activities. The HVAC system includes a bank of high-grade filters at the air intakes that can be used during hazard conditions. Employing triggered high-grade filtration that is effective only for limited time period reduces the LCC of providing high-grade filtration by comparison to full-time filtration.

The HaLT/HEPS HVAC strategy is summarized in Table 5. Prior to the attack, the auditorium is kept in an overpressurized state to prevent leakage in while

Table 4: Building Protective Factor and Untreated Fatality Factor for Selected HVAC Building Protection Strategies

HVAC STRATEGY	FILTRATION RATE	BUILDING PROTECTION FACTOR	UNTREATED FATALITY FACTOR
Normal	30%	1.3	87%
Normal/Off/Normal	any	2.6	59%
Overpressure	80%	6.2	39%
Normal/Off/Purge	any	6.6	35%
Overpressure/Minimal/Purge	80%	32.8	12%
Overpressure/Minimal/Purge	90%	65.6	7%
Overpressure/Minimal/Purge	95%	131.1	4%

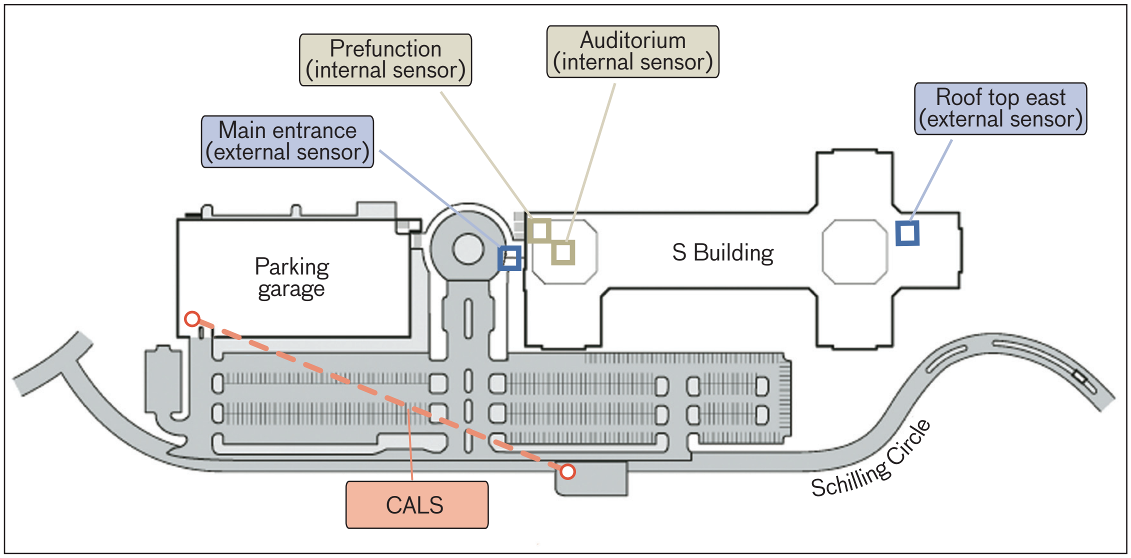

FIGURE 7. In the HaLT sensing method, the chemical-agent line sensor (CALS) monitors plumes of agents prior to their arrival at Lincoln Laboratory South building. The building units are point sensor nodes for biological and chemical detection.

providing normal air exchange. For external biological or filterable chemical attack, the response is to close any open doors, turn on filtration, and maintain overpressurization. After the attack has passed, the HVAC system enters Purge mode. If the attack is an external nonfilterable chemical, then the auditorium enters the Isolation mode by closing all doors and the intake/exhaust dampers. If the attack is an internal chemical or biological agent, then the auditorium HVAC is placed in the Purge mode, and the surrounding areas are placed in Overpressure mode. Figure 9 shows good agreement between HaLT/HEPS HVAC model predictions and measured releases of CO_2 gas as stimulant, with a purge implemented at 30 minutes.

Let us revisit the benchmark cases of the Lincoln Laboratory South Laboratory auditorium vulnerabilities (as presented earlier in Figures 4 and 5), but now with HaLT/HEPS active protection enabled. Figure 10 shows the protection provided by HaLT/HEPS triggered filtration against outdoor *Ba* release. For this figure, the subfigures show the two panes as before, plus panes showing the CCS and auditorium filtration system status. In this configuration, we assume that there is an intake duct

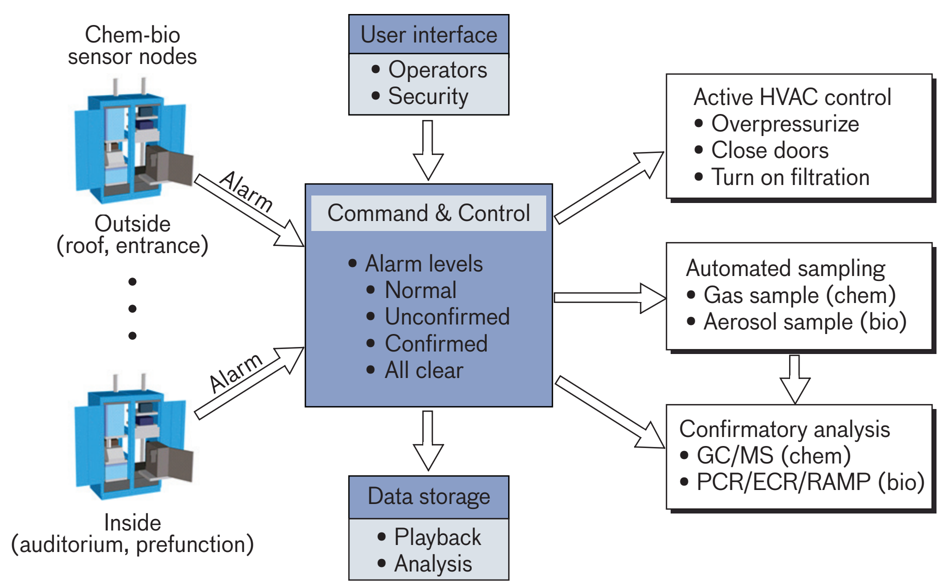

FIGURE 8. When a sensor issues an alarm, the Command and Control system carries out a set of scripted actions determined by alarm type and location. These actions include automatic changing heating, ventilation, and air conditioning (HVAC) modes, automatic sample collection, and operator notification for manual sample processing. GC/MS is gas chromatograph/mass spectrometry, PCR is polymeric chain reaction, ECR is electrochemical luminescence, and RAMP is a commercial product.

Table 5: HaLT/HEPS* HVAC Protective Strategies

ATTACK LOCATION	PRIOR TO ATTACK	DURING ATTACK	AFTER ATTACK
External (filterable)	Normal with Overpressure	Filter with Overpressure Switch HEPA filter on Close doors Maintain overpressure (Aud > Pre > Lobby)	Purge Full fresh air, all zones
External (non-filterable)	Normal with Overpressure	Isolation Close dampers & doors Shut down HVAC	Purge Full fresh air, all zones
Internal	Normal with Overpressure	Purge attack zone Overpressure adjacent zones	Purge Full fresh air, all zones

* HaLT/HEPS stands for Hanscom-Lincoln Testbed/Hazardous Environment Protection System

that extends across the South Laboratory to the east end of the building. The function of this duct is to provide for a delay between sensing the attack and entry of the agent into the building. Note that when the plume reaches the west sensor node at 2.5 minutes after the release, the CCS closes the auditorium doors, switches the auditorium HVAC to Overpressure mode, and turns on the auditorium HEPA filtration system. By 5.5 minutes after the release, contamination has begun in the prefunction area (which is not fitted with HEPA filtration) but the auditorium air remains safe. Sampling of the outside air is automatically triggered when the external biological sensors alert, and testing is initiated to confirm the attack. In actual bio-attacks, medical treatment would be enhanced because we would have reduced exposure and would have confirmed the exact strain of agent.

Figure 11 shows the corresponding HaLT/HEPS active protection against an indoor sarin (GB) release. Approximately one minute after the chemical trigger sensor monitoring the prefunction area exceeds the detection threshold, the CCS responds by closing the auditorium doors, turning on filtration, and maintaining overpressure.

Future Implications

As we have seen in the HaLT/HEPS case studies, the ability to place indoor sensors near the point of release enables rapid, effective HVAC response. The nearer the sensor is to the point of release, the less sensitive it need be for a given agent amount. Other studies have shown a high degree of utility for indoor point sensors with trigger thresholds as high as 1000 ppl, assuming they are within approximately 100 ft of point of release. Achieving this high density of indoor trigger sensors requires that they be low cost and low maintenance. For effective rapid trigger coverage outdoors, remote sensors are particularly attractive because they can provide advance warning of contaminant before it impacts the building. Similarly to the indoor scenario, remote sensors do not need be extremely sensitive if they can observe the release near its release point. In the absence of remote sensors, point sensors at the building air intakes can be

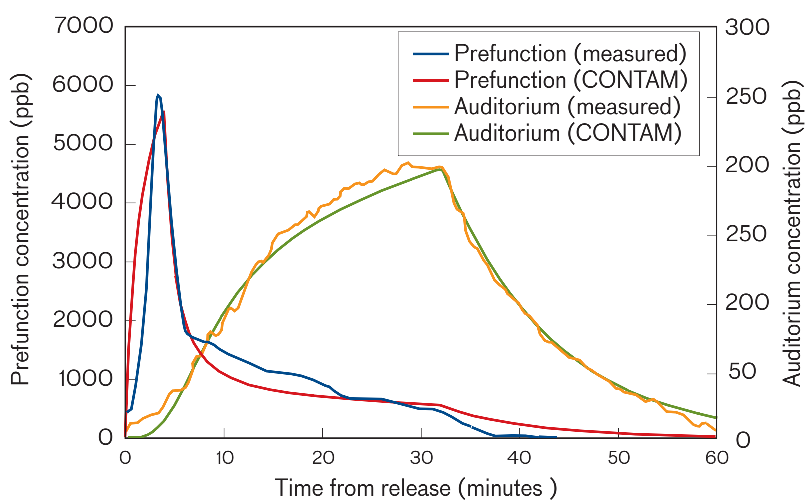

FIGURE 9. There is excellent agreement between the measured and modeled concentrations for a release of CO_2 gas in the prefunction and auditorium areas with the auditorium HVAC switched to Purge mode 30 minutes after release. CONTAM is a modeling program developed at the National Institute of Standards and Technology.

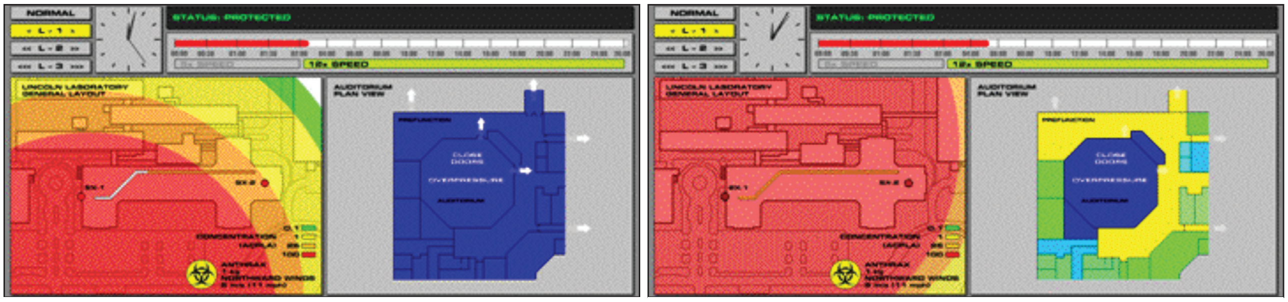

FIGURE 10. The auditorium and prefunction area concentrations are significantly reduced for 1 kg *Ba* attack with active HaLT/HEPS response. Comparing these images to those in Figure 4, we see that even after 6 minutes (in the image on the right), the HaLT/HEPS response keeps the contamination level in the Auditorium at AEGL-1. In the lower right of the left side of each image is the representation of the command and control system and the status of the auditorium filtration system.

effective but may require alternate air intakes to account for the delay in trigger sensing.

Resolving triggered events requires rapid contaminant identification with low false-positive rate. This capability enables fast return to normal operations and minimizes impact to building operations for false positives. Some buildings have employed an integrated sample-collection manifold system of aspirated pipes to further extend the coverage of rapid identifier sensors. Although it is not yet a part of HaLT/HEPS, such a sampling manifold, if implemented in new construction, need be no more expensive than the host of other utility infrastructure such as fire suppression sprinklers.

The effectiveness of HVAC isolation and purge modes is strongly dependent on HVAC zone configuration. Proper use of firestops and hallway segmentation using triggered hallway doors can be very effective. A tight exterior building envelope is useful because it provides more effective means of maintaining internal overpressure and thereby decreasing infiltration from external contamination. Finally, high-capacity exhaust that can be directed to points of likely indoor release is needed to purge indoor contaminants.

In the event of a confirmed contamination of a building, emergency response will follow automated building actions. Coordination and understanding of respective

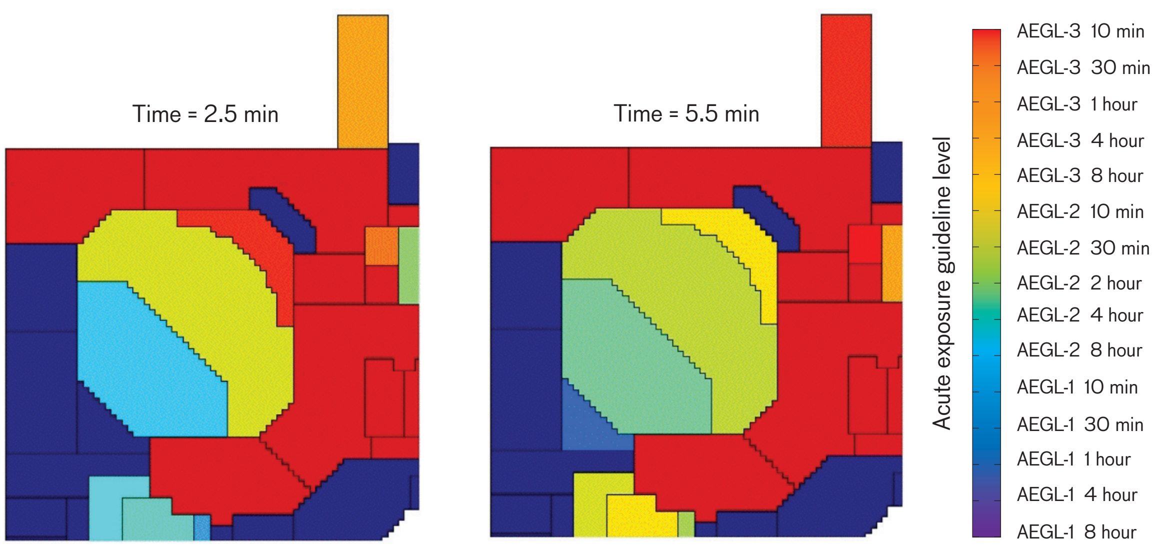

FIGURE 11. A release of 1 kg sarin in the prefunction area clearly has an impact. The chemical trigger sensor monitoring the prefunction area almost instantly exceeds the 0.03 mg/m^3 detection threshold. However, active HVAC response limits the auditorium dosage to not exceed the AEGL-1 level over 1 hour. Compare these figures to those in Figure 5 to note the positive effects of the HaLT/HEPS response.

roles and responsibilities are important. The local building manager and security services, who will generally be responsible for evacuation, need to have a protective action plan in place and have trained personnel to implement it. Currently, decision support software tools are being developed to assist decision makers manage the potentially inconsistent and confusing data that may accompany a contamination event. Local police and fire departments, operating under municipal government, will be first responders and begin the emergency management and direct involvement of local medical facilities for treatment. Attention to triaging and treating the injured as well as preventing further injuries is warranted. The Army National Guard provides civil support teams operating under the governor of each state for specialized hazardous materials responses. Finally, federal agencies, including the Department of Homeland Security (DHS) and the Department of Justice, will direct the post-attack characterization, collection, and preservation of evidence and criminal prosecution. Building owners, with guidance from the DHS, must be expected to direct decontamination efforts and resumption of function.

Although the initial focus in building protection has been implementing in existing construction, it is clear that both improved protective capability and reduced cost can be achieved in new construction. Surprisingly, no standards exist for airborne hazard protection in new construction. For the time being it will remain the responsibility of building owners and managers to decide how much protection is warranted and how best to achieve it. Testbeds such as HaLT/HEPS and modeling tools such as the Building Protection Toolkit are available for evaluating new concepts. Because of security concerns, actual building protection implementations in operating high-value facilities remain inaccessible as design cases. Some specialized commercial firms have been established to provide protective building services, such as BioONE in Boca Raton, FL, but widespread acceptance is still in the future.

The current acceptance of this technology is limited by cost and performance of sensors and perception of risk mainly to high-value government headquarters buildings. If releases directed against commercial buildings do occur, demand will certainly extend to other classes of buildings. Commercial office space with integrated protection against airborne contamination may command higher rent from tenants than for those spaces without such protection. Other factors that may affect widespread acceptance are emerging building codes and regulations and pressure from insurance entities for reducing exposure to cleanup costs. Integration with advanced fire suppression systems, advanced energy management systems, and integrated security systems are inevitable and will lead to enhanced efficiency, reliability of operations, and potential lives saved.

Acknowledgments

The authors wish to thank the following for their contributions to this article: Sandy Wilson and Rose Joseph for their work on HaLT/HEPS modeling; Moses Ting and Tim Moshier for HaLT/HEPS engineering; Gerry Larocque for protective strategies; Dave Tremblay and Amanda Goyette for sensor measurements; Paul Benda of the Pentagon Force Protection Agency, CBRN Directorate, and Teresa Lustig of the Department of Homeland Security for technical guidance on related projects.

This work was supported by the Director of Defense Research and Engineering. ■

REFERENCES

1. W.J. Kowalski, *Immune Building Systems Technology* (McGraw Hill, New York, 2003).
2. Defense Threat Reduction Agency, "Hazard Prediction and Assessment Capability (HPAC)," www.dtra.mil/rd/programs/acec/hpac.cfm.
3. M. Tewari, F. Chen, T.T. Warner, W.J. Coirier, and S. Kim, "Numerical Modeling Study of Wind Flow over the Salt Lake City Region Using Integrated WRF-Noah-UCM Model at Meso-Gamma Scale," UCAR, www.mmm.ucar.edu/wrf/users/workshops/WS2005/presentations/session4/3-Tewari.pdf.
4. Conjunction of Multizone Infiltration Specialists (COMIS), Energy Performance Buildings Group, http://epb.lbl.gov/comis/users.html.
5. W. Bryden, Building Protection Toolkit, www.darpa.mil/sto/chembio/pdf/BPTK.pdf.
6. Army Corps or Engineers, "Protecting Buildings and Their Occupants from Airborne Hazards, TI 853-01, Engineering and Construction Division, Directorate of Military Programs," Washington, D.C., Oct. 2001, p. 22, www.nd.gov/des/homeland/docs/building-protection.pdf.
7. Environmental Protection Agency, "Building Air Quality: A Guide for Building Owners and Facility Managers," www.epa.gov/iaq/largebldgs/baqtoc.html.
8. Whole Building Design Guide, Chemical/Biological/Radiation (CBR) Safety of the Building Envelope, www.wbdg.org/design/env_cbr_safety.php.

9. U.S. Army Corps of Engineers, "Design of Collective Protection Shelters to Resist Chemical, Biological, and Radiological (CBR) Agents," Engineer Technical Letter 1110-3-498, Dept. of the Army, Washington. D.C., Feb. 24, 1999.
10. W. Blewett and R. Heiden, "Protecting Buildings and Their Occupants from Airborne Hazards," TI 853-01, U.S. Army Corps of Engineers, Engineering and Construction Div., Directorate of Military Programs, Washington, D.C., Oct. 2001.
11. Dept. of Health and Human Services, Centers for Disease Control and Prevention, Natl. Inst. for Occupational Safety and Health, "Guidance for Filtration and Air Cleaning Systems to Protect Building Environment from Airborne Chemical, Biological or Radiological Attacks," DHHS (NIOSH) Pub. No. 2003-136, Cincinnati, Apr. 2003.
12. Dept. of Health and Human Services, Centers for Disease Control and Prevention, Natl. Inst. for Occupational Safety and Health, "Guidance for Protecting Building Environments from Airborne Chemical, Biological, or Radiological Attacks," DHHS (NIOSH) Pub. No. 2003-139, Cincinnati, May 2002.
13. Health guidance for CBR agents, Centers for Disease Control and Prevention, www.cdc.gov.
14. Airflow and Transport Pollution Group, Advice for Safeguarding Buildings against Biological Attack, http://securebuildings.lbl.gov.
15. Raman-Shifted Eye-Safe Aerosol Lidar (REAL), Earth Observing Laboratory, www.eol.ucar.edu/lidar.
16. WindTracer, Lockheed Martin, www.lockheedmartin.com/products/WindTracer/index.html.
17. Mobile Chemical Agent Detector (MCAD), Mesh, Inc., www.meshoxford.com/mcadmilestones.htm.
18. J.A. Seeley and J.M. Richardson, "Early Warning Chemical Sensing," in this issue.
19. T.H. Jeys, W.D. Herzog, J.D. Hybl, R.N. Czerwinski, and A. Sanchez, "Advanced Trigger Development," in this issue.
20. AirSentinel, ICX Mesosystems, www.mesosystems.com/AirSentinel.html.
21. M.S. Petrovick, J.D. Harper, F.E. Nargi, E.D. Schwoebl, M.C. Hennessy, T.H. Rider, and M.A. Hollis, "Rapid Identifiers for Biological-Agent Identification," in this issue.
22. Jeys, "Advanced Trigger Development."
23. Lawrence Livermore National Laboratory, "When Every Second Counts," www.llnl.gov/str/September03/pdfs/09_03.3.pdf.
24. DSQ/GC MS, Thermo Scientific, www.thermo.com/com/cda/product/detail/0,1055,18759,00.html.
25. C.A. Primmerman, "Detection of Biological Agents," *Linc. Lab. J.*, vol. 12, no. 1, 2000, pp. 3–32.
26. Centurion, Smiths Detection, www.smithsdetection.com/eng/1470.php.
27. Seeley, "Early Warning Chemical Sensing."

ABOUT THE AUTHORS

Daniel Cousins is the assistant leader of the Biodefense Systems group, which develops advanced technology and protection against biological and chemical threats. After joining Lincoln Laboratory in 1987, he has contributed to and led programs involving the development of electro-optical sensors for aerospace, missile defense, and meteorological applications. He is the Lincoln Laboratory program manager of the Pentagon Shield and Urban Shield programs, which provide protection against biochemical threats to government building occupants throughout the National Capital Region. He received a bachelor's degree from Miami of Ohio, a master's from Yale University, both in physics, and a doctorate in aerospace systems from MIT.

Steven D. Campbell is a senior staff member in the Advanced Systems Concepts group. He has been working since 2002 on bioterrorism analysis and biosensor development, including the Biological Agent Sensor and Trigger (BAST) program. Previously, his Lincoln Laboratory research included projects related to air traffic control, the Global Positioning System, and weather sensing radar. He received his doctorate in electrical engineering from the University of Washington and joined Lincoln Laboratory in 1978.