IMMUNE-BUILDING TECHNOLOGY and Bioterrorism Defense

A review of the effectiveness of dilution ventilation, filtration, and ultraviolet germicidal irradiation in mitigating five biological-weapon agents

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Events following Sept. 11, 2001—particularly the anthrax mail scare—heightened awareness of the threat of bioterrorism. One method of dealing with this threat is the application of immune-building technologies. Immune buildings are those that suppress or resist harmful microbial contamination—airborne or otherwise. The primary immune-building technologies for controlling airborne pathogens are dilution ventilation, filtration, and ultraviolet germicidal irradiation (UVGI). This article reviews the effectiveness of these technologies in mitigating the threat to occupants posed by the release of five representative biological-weapon (BW) agents in a model multistory building's outside-air intakes. A comparison of the predicted casualties with and without air-cleaning technologies installed provides a basis for evaluating the limits of protection.

Immune buildings incorporate technologies that actively or passively protect occupants from airborne microbial contaminants.

BIOLOGICAL WEAPONS

Any microorganism that causes disease or produces toxins can be used as a biological weapon. For design purposes, the following can be used to represent the entire array of possible BW agents:

- Anthrax spores, which are relatively easy to filter, but resistant to UVGI—except at very high doses.[1]
- Smallpox, which is one of the most penetrating microorganisms for filters, but highly susceptible to UVGI.
- TB bacilli, which are mid-sized bacteria removable by either filtration or UVGI.
- Influenza, a small virus of variable lethality that has caused epidemics around the world.
- Botulinum toxin, which is the deadliest toxin known and used to represent many other toxins that might be used as BW agents.

Toxins are poisonous compounds produced by plants,

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animals, bacteria, and other natural sources. In weaponized form, they typically are powders consisting of particles in the size range of approximately 0.9 to 5.8 microns. The size distribution of powdered toxins is lognormal, and the logmean size is approximately 2.2 microns.[2] Particles in this size range are removable at rates approaching 100 percent by MERV 13 to 15 filters.[3] Studies indicate that UVGI can break down some toxins; however, insufficient data is available; therefore, botulinum is assumed to be completely resistant to breakdown under UVGI exposure.

The properties of the five design-basis agents selected for analysis are shown in Table 1. The logmean diameters determine the filtration rate for any model filter.[4] The UVGI rate constants were computed based on the referenced laboratory studies.[5] The UVGI rate constant of smallpox is assumed to be the same as that of the closely related Vaccinia virus.[7]

Agent	Mean diameter, μm	UVGI rate constant, $cm^2/\mu W\text{-}s$	Reference(s)
Bacillus anthrax spores	1.118	0.000031	1, 2, 4
TB bacilli	0.637	0.002132	2, 4, 6
Smallpox virus	0.224	0.001528	2, 4, 7
Botulinum toxin	2.24	Unknown	2
Influenza A virus	0.098	0.001187	2, 4, 8

TABLE 1. Properties of design-basis BW agents.

BUILDING-ATTACK SCENARIOS

Typical scenarios for an attack on an office building include an outside-air release, a release in the outside-air intakes, a release in the air-handling unit (AHU), and a release in a general area of the building.[9,10] These releases may be sudden, as when an agent is dumped into air intakes, or may occur gradually, as when a spraying device is placed inside a building. The outside-air-intake-release scenario is one of the most commonly discussed scenarios because many buildings have intakes at ground level, as shown in Photo A.

Figure 1 illustrates the outside-air-intake-release scenario. In general, a release into outside-air intakes would pose a greater threat to occupants than would any other kind of release because most, if not all, of the agent would enter the ventilation system and be distributed throughout the zones served by the system.

If an AHU contains air-cleaning

PHOTO A. Ground-level outside-air intakes may be vulnerable points for many buildings.

equipment such as filters or UVGI, concentrations may be reduced dramatically. In both an outdoor release and air-intake release, a large fraction of the BW agent may be removed on the first pass through a filter unit, with the remaining concentration reduced through purging and recirculation over time.

If a BW agent were released in a general area of a building, such as a lobby or atrium, concentrations would be high in the vicinity of the release, but considerably lower elsewhere. Although the agent would recirculate, it also would be exfiltrated or purged at the normal building outside-airflow rate. Concentrations in the release area would remain high until the agent was purged, while the concentrations in other areas would not reach levels as high as those in the air-intake-release scenario. This may not always hold true for large internal auditoriums and atria or where stack effects play a major role in redistributing airflows. In general, a release inside an AHU downstream of the filters would produce the highest overall airborne concentrations in a building, which is good reason to lock equipment rooms and restrict access.[10]

AIR-CLEANING SYSTEMS

Three primary air-cleaning technologies are in use today: air purging, filtration, and UVGI. Air purging is a function of any ventilation system that uses outdoor air. Systems that employ 100-percent outdoor air, such as those of many health-care facilities, have a natural advantage against internal releases, depending on the air-change rates. Removal by dilution ventilation purges all BW agents at the same rate, if we conservatively ignore plate-out and settling rates. Plate-out may cause longer-term hazards and affect remediation in the aftermath of an attack; however, this review addresses initial effects only. In this example, the outside-airflow rate is 15 percent of the total ventilation-system airflow.

Filtration can be highly effective at removing most BW agents. The removal rate of any filter can be estimated from vendor performance curves or minimum-efficiency-reporting-value (MERV) test results.[3,11] Table 2 shows estimated filtration rates of six types of MERV-rated filters, based on models of MERV test results from two filter manufacturers.

Table 2 also summarizes the removal, or kill, rates of different levels of UVGI exposure, which are characterized by UVGI rating values (URVs). The dose is the average intensity multiplied by an exposure time of 0.5 sec, which is representative of many typical UVGI systems. URV is a proposed rating system consisting of 20 gradations of average UVGI intensity. URV ratings parallel MERV ratings and provide a convenient way to match filters and UVGI systems for aerobiological applications. The use of air-cleaning components with similar MERV and URV ratings offers balanced removal rates across the entire array of

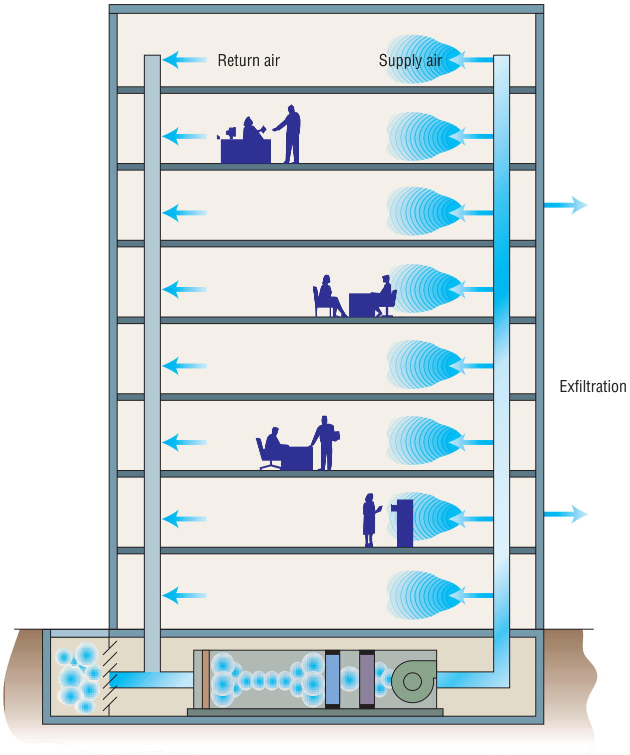


FIGURE 1. In the air-intake-release scenario, all of the agent enters the building and is distributed via the ventilation system.

Filter Rating	**MERV 6**	**MERV 8**	**MERV 10**	**MERV 13**	**MERV 15**	**MERV 16**
Bacillus anthrax spores, %	15.5	36.7	39.2	96.3	99.979	99.981
TB bacilli, %	7.4	18.1	19.5	78.6	98.0	98.1
Smallpox virus, %	3.7	7.4	7.9	39.6	68.0	70.6
Botulinum toxin, %	34.6	69.9	76.3	99.986	100	100
Influenza A virus, %	6.2	11.2	12.0	46.229	71	76
UVGI System Rating	**URV 6**	**URV 8**	**URV 10**	**URV 13**	**URV 15**	**URV 16**
Average intensity, μW/cm^2	75	150	500	2,000	4,000	5,000
Dose (t = 0.5 s), μW-s/cm^2	37.5	75	250	1,000	2,000	2,500
Bacillus anthrax spores, %	0.4	0.8	1.5	3.1	6.0	8.9
TB bacilli, %	23.4	41.3	65.6	88.1	98.6	99.8
Smallpox virus, %	17.4	31.8	53.4	78.3	95.3	99.0
Botulinum toxin, %	0	0	0	0	0	0
Influenza A virus, %	13.8	25.7	44.8	69.5	90.7	97.2
MERV/URV Rating	**6/6**	**8/8**	**10/10**	**13/13**	**15/15**	**16/16**
Bacillus anthrax spores, %	15.9	37.2	40.2	96.4	99.980	99.983
TB bacilli, %	29.1	52.0	72.3	97.5	99.972	99.997
Smallpox virus, %	20.4	36.8	57.1	86.9	98.5	99.7
Botulinum toxin, %	34.6	69.9	76.3	99.986	100	100
Influenza A virus, %	19.2	34.0	51.4	83.589	97	99

TABLE 2. Removal rates for design-basis BW agents.

possible BW agents, provided the exposure time is approximately 0.5 sec.

Combinations of filters and UVGI are referred to here as MERV/URV systems for convenience. The air-cleaning efficiency of various MERV/URV systems is shown in Table 2. The fractional air-cleaning efficiency, R_{tot}, is the complement of the product of the fractional penetration of the filter, P_f, and UVGI system, P_u, as follows:

$$R_{tot} = 1 - \left(1 - P_f\right)\left(1 - P_u\right)$$

SIMULATION RESULTS

A single well-mixed zone served by a recirculating air-distribution system was modeled to test the effectiveness of various air-treatment strategies. The single-zone model has an outside-airflow rate that is 15 percent of supply airflow, and no credit is taken for removal rates because of the air-handling equipment or plate-out on building internal surfaces. In reality, most buildings would be modeled more accurately as multizone systems with stairwells, elevator shafts, wall leakage, and stack effects; so the present model is simply an idealized first approximation. However, multizone modeling of buildings using the CONTAMW indoor-air-quality- and ventilation-analysis computer program[12] shows similar results and produces the same general conclusions regarding air-cleaning-system size.

The attack scenario in this simulation was a sudden release in the outside-air intakes. A transient single-zone model was used because each zone would see the same airborne concentrations. The predicted casualties were based on a generic epidemiological model, with the baseline condition preset to produce 99 percent casualties—that is, the quantity released into the building was adjusted to produce 99 percent casualties in the baseline condition. The actual quantities used are not published here, nor should they be.

The predicted casualties represent first infections only; no secondary infections were accounted for in this model. The predicted casualties were determined by assuming a breathing rate of 0.02 cu m (0.71 cu ft) per minute for all occupants and 90-percent lung-absorption efficiency.[13] Modeling was performed computationally by evaluating the building airborne concentrations minute by minute.

Figure 2 shows the results of the simulations. The baseline casualties of 99 percent were reduced to the values shown by the indicated MERV/URV systems. A MERV 13/URV 13 combination resulted in approximately zero casualties for all BW agents and no further increases in air-cleaning efficiency. Obviously, this combination provides considerable protection for building occupants under the outside-air-intake-release scenario. Simulations of other attack

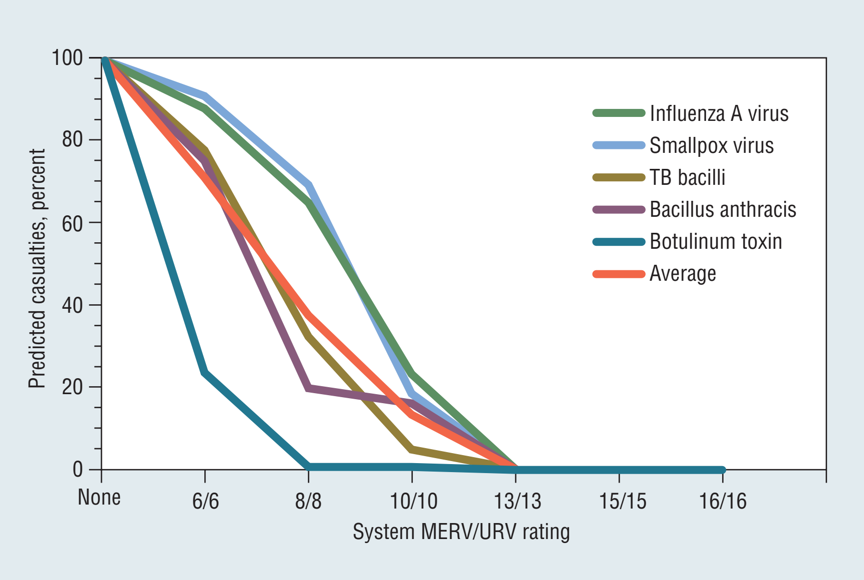


FIGURE 2. The effect of increasing filtration and UVGI power on predicted casualties.

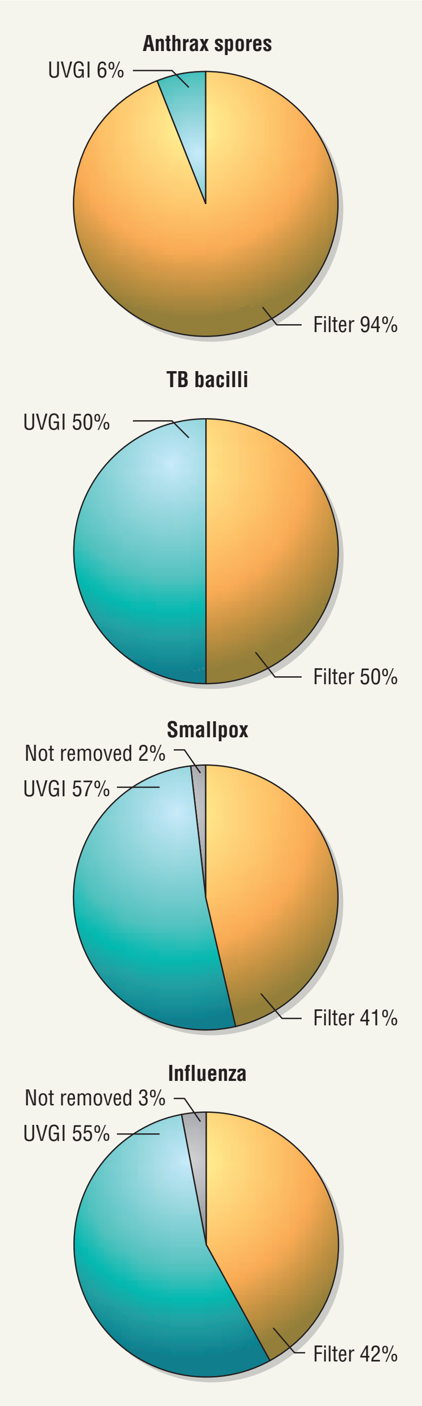


FIGURE 3. Breakdown of removal rates for a MERV 15/URV 15 system.

scenarios and other building types do not all produce zero casualties, but do suggest that the performance of air-cleaning systems levels off before reaching the MERV 15/URV 15 range.[2]

The diminishing-returns effect illustrated in Figure 2 leads to the conclusion that, for any given building, there is only one appropriate air-cleaning-system size, and that size is independent of the BW agent tested and the attack scenario considered. The size of a MERV/URV system primarily is a function of ventilation flow rate and building volume. Removal rates can be increased further by increasing the total airflow rate or the outside-airflow rate; however, this can be costly.

Although further research is needed to examine a variety of real-world buildings—including their leakage rates and stack and filter-bypass effects—considerable protection appears to be achievable with relatively modest air-cleaning systems. Considering the removal rates obtainable with the individual components in Table 2 and the effects of 15-percent outside-air dilution, this should not be too surprising.

In a MERV/URV system, it is of interest to know what fraction of the air cleaning is being done by the filter and what fraction is being done by the UVGI. Figure 3 shows a breakdown of the removal rates of a MERV 15/URV 15 system. Note that the filter does most of the work for anthrax, but the UVGI does most of the work for smallpox.

The simulation summarized here is but one example for a particular building type. Results may vary with other buildings, weather conditions, and attack scenarios and especially large auditoriums. Information on other types of buildings and attack scenarios, as well as other technologies for dealing with chemical and BW agents, is available in the references listed at the end of this article.

THE MLGW RETROFIT

In response to concerns about bioterrorism, Memphis Light, Gas, and Water (MLGW) retrofit a UVGI system in its administration-building ventilation system to augment the existing air-cleaning train, which consisted of a roll prefilter, a high-efficiency pleated filter, and carbon adsorbers. Ten UV-lamp assemblies, each with a total of 204 UV watts, were distributed through the five-story air chases, through which building return air was drawn into the air-handling units. Advantage was taken of the available space and the ease of walk-in maintenance. The lamp assemblies were surrounded with 4-ft-by-6-ft polished aluminum reflector plates to boost intensity and distribute it more evenly.

A second battery of UV lamps was added inside each of the five air-handling units (Photo B). The total UV power in the AHUs varied from 816 to 1,632 w, while airflow varied from 12,200 cfm to 92,600 cfm. Design velocity in each system was approximately 500 fpm. The total exposure time in the AHU assembly was approximately 0.3 sec.

The combination of the UVGI and filters was calculated to destroy or remove at least 70 percent of anthrax spores. The system also was predicted to destroy 99.99 percent of smallpox virus and 99.999 percent of TB bacilli. Based on a single-zone simulation, this system should offer considerably improved protection to most building occupants following an air-intake release of any BW agent. Data is being collected by MLGW to determine if any significant reduction in respiratory-disease incidence and allergy symptoms is occurring as a result of the air-cleaning-system enhancement.

SUMMARY/CONCLUSIONS

Results of the analysis summarized

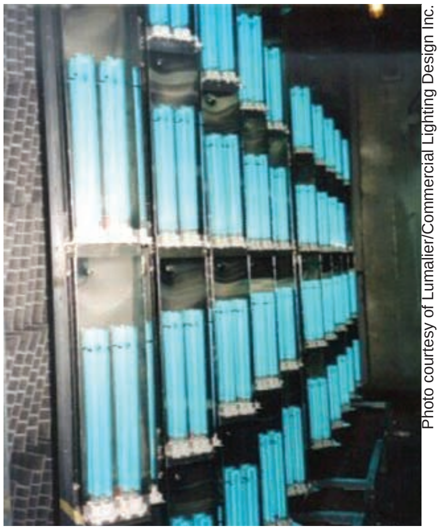


Photo courtesy of Lumalier/Commercial Lighting Design Inc.

PHOTO B. A high-power UVGI system installed in an air-handling unit of the MLGW administration building.

here suggest that significant protection can be provided to building occupants by retrofitting modest air-filtration and UVGI air-disinfection systems. Although this may not offer complete immunization against all possible terrorist attacks, the number of potential casualties can be reduced to a minimum in a cost-effective manner.

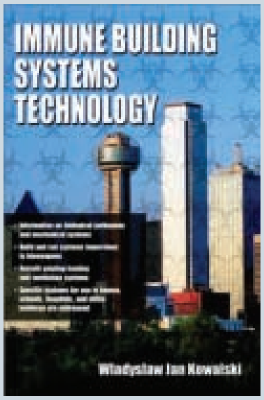
Retrofitting air-cleaning systems with higher removal rates has been shown to bring diminishing returns because of the limitations imposed by building-ventilation-system characteristics. This leads to the conclusion that only one size air-cleaning system is appropriate for any given building, a fact that simplifies the choice of air cleaning for most buildings and scenarios. This is analogous to the way in which there is only one cooling- or heating-coil size that is right for any building. The conclusions drawn from the foregoing analysis generally will be true for typical office buildings with forced air, but may not be true for all buildings or all types of ventilation systems. Case-by-case evaluation is needed to find the most cost-effective system for a particular building.

Collateral benefits are possible because any building immunized against BW agents is able to handle everyday microbes as well. The authors hope that the immune-building technologies discussed in this article are never put to the test by anything worse than the common cold.

‘One-Stop Reference’ Available

Information on the design, construction, and maintenance of systems used to protect buildings against biological and chemical weapons is available in W.J. Kowalski’s new book, “Immune Building Systems Technology.”

Published by McGraw-Hill in September, “Immune Building Systems Technology” is said to be the first book to offer detailed coverage of both airborne pathogens and the mechanical systems used to control indoor-air quality.



The book, Kowalski says, “provides a detailed database of chemical and biological weapons and presents the history of their use. The modeling of buildings and ventilation systems is treated in detail, and simulated biological attacks on many types of buildings are summarized. The predicted effectiveness of air-cleaning technologies is demonstrated by comparison of estimated casualties under various attack scenarios. Various technologies are covered, including filtration, UVGI, ozone, and pulsed light. Other subjects include mail-disinfection systems, decontamination and remediation of buildings, control systems, risk estimation, epidemiology, and the economics of air cleaning. Building vulnerabilities are discussed, and security and emergency procedures are addressed, as are guidelines for sizing building-protection systems.”

For more on the book, visit Amazon.com.

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