The Use of UV-C for Improved Indoor Air Quality: Experiments and Modeling Application for Homeland Security Issues

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ABSTRACT

Disinfection experiments were performed using a custom built 0.46 × 0.46 m (cross-section) by 4.3 m long wind tunnel fitted with a commercially available UV-C lamp unit operated under conditions usually found in HVAC systems (air velocities of 2000-9500 m/h = 130-550 feet/min). Four test organisms were selected. One bacteria, a wild type *Escherichia coli* (wild type W3110), and three fungi spores: *Penicillium aragonense* ATCC #42228, *Rhodotorula glutinis* ATCC #32765, and *Cladosporium sp*. ATCC #32720, the latter three being common air biocontaminants. Disinfection of E. coli proved to be extremely effective, with more than 98% of the input *E. coli* killed under various conditions. As expected, disinfection was greater with two UV lights on and at low airflow rates. High relative humidity reduced the efficacy of the disinfection process (95% killed at 97% RH vs 99+% at RH lower than75%). Disinfection of the fungal spores was much more difficult and exhibited more data scattering. A simple model was developed to correlate the experimental data with simple exponential decay based on UV power consumption (i.e., irradiation), exposure time in the wind tunnel, and the specific test organisms. Next, a second model served to predict the expected reduction in indoor bioaerosol concentration for a given building/house etc. depending on the various operating parameters such as the number of UV lights, airflow, source contamination, etc. In particular relevant to Homeland Security was the modeling of the protection of commercial buildings against crop dusting of bioterrorism agents such as anthrax spores using duct mounted UV-C lamps. The model helped in understanding what parameters were most important in developing a strategy to protect buildings from attacks, and maximizing the benefits of UV, while minimizing the energy and equipment costs. The different scenarios showed that germicidal UV can be an effective tool in meeting safe building levels.

INTRODUCTION

Ultraviolet light (UV) is widely used for drinking water disinfection, but deployment of UV for air disinfection remains relatively scarce. The main reason is the lack of understanding of the basic design rules for UV air disinfection. This is unfortunate as UV can effectively kill a wide range of microorganisms such as bacteria, fungal spores and viruses. There are several challenges to the proper deployment and design of UV air disinfection. These include:

- The lack of detailed information on the death/deactivation kinetic parameters for the different biocontaminants of interest. It is generally agreed that death kinetics for microorganisms follows an exponential decay. Yet, most death rate constants have been obtained in water or on a solid media, and their utilization for airborne organisms is questionable.

- The complex aerodynamics of HVAC systems, in particular high air velocities leading to turbulent flow, and flow heterogeneities, complex geometries, leading to non-developed air flow velocity profiles.

- Non ideal factors difficult or impossible to account for, such as dust accumulation on surfaces, very complex geometries, e.g., coils, drip pans, etc.

However, UV air disinfection can be very effective in disinfecting indoor air, and both capital and operating costs are very economical. There are numerous examples, either documented scientifically, or anecdotically of major health benefits, reduction of nosocomial infections in hospitals, improvement of indoor air quality, after installation of UV air disinfection systems. For these reasons, it is reasonable to believe that germicidal UV has a role to play in Homeland Security and in safe building technology. However, a better understanding of the efficacy of UV air disinfection as well as the actual application and treatment goals are required before deployment of UV in that context.

The present paper discusses experimental testing of germicidal UV, and of its application in Safe Building Technology. Experiments on actual air disinfection using germicidal UV are presented. The results are then used to develop simple models that describe air disinfection kinetics and application of UV is various settings, in particular for personal and public protection against bioterrorism attacks.

MATERIALS AND METHODS

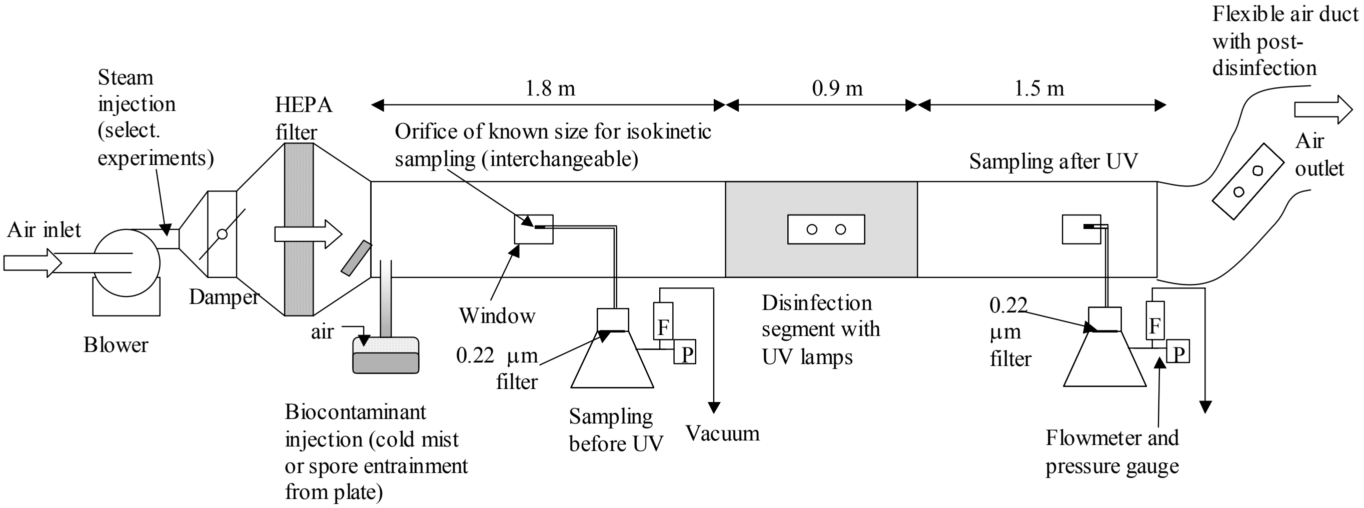
Test Bench

The efficacy of biocontaminant disinfection by germicidal UV was tested using a custom made wind tunnel consisting of a blower, biocontaminant generation section, and a UV disinfection section. A schematic of the test bench is shown in Figure 1. The test bench was designed to emulate actual condition of use of germicidal UV in commercial or residential buildings. With the exception of the disinfection section, the wind tunnel (total length of 4.25 m) was build of 0.46 × 0.46 m (1.5 × 1.5 feet) cross-section galvanized steel (HVAC quality, 0.8 mm thick). The disinfection section (0.9 m long) was made of aluminum, as it had been reported that aluminum is more UV reflective than galvanized steel. The aluminum (1.6 mm thick) on the UV disinfection section was not polished, but prior to the experiments, it was carefully cleaned and degreased.

The test bench included a fixed speed 1.5 HP blower, and dampener to regulate the air flow (500-2000 $m^3 h^{-1}$). In order to avoid interference with dust or other contaminants, the influent air was filtered through a 99.97% efficiency rated HEPA filter.

Injection of the biocontaminant was either as bioaerosol or as airborne spores. In the latter case, Petri dishes with sporulating molds were directly mounted into the inlet air stream immediately after the HEPA filter. The concentration of spores in the air was varied by changing the number of plates in the duct. For bioaerosol generation, a residential cold-mist humidifier was used, in which a suspension of the test organism was placed. The exhaust of the humidifier was directed into the main air stream. A small constant air stream of sterile-filtered air was added to the humidifier improve carry over of the bioaerosol to the wind tunnel. The concentration of bioaerosol was adjusted by changing the concentration of the cell suspension. The cold mist humidifier was placed on a scale to monitor supply of the bacterial or spore suspension. The size of the bioaerosol droplets was not measured but is believed to be very small (5-20 µm).

Figure 1. Schematic of the UV lamp disinfection test bench unit (not to scale, and not all analytical devices are shown).



UV-C Lamps and Disinfection Section

Germicidal UV was generated with a duct mounted AiraBella UV-C unit 1999 model (US Pat: 5,903,552; Indoor Air Technology, San Bernardino, CA). The unit used for the tests consisted of a duct mounted power supply and two 18 W Philips TUV bulbs. The unit was positioned such that the bulbs (19 cm long) were normal to the air flow, and located at mid height of the duct. The first and second bulbs were position at 39 cm and 70 cm from the beginning of the disinfection segment, respectively. For experiments with one bulb, only the second one was turned on. The bulbs where wiped clean prior to each experiment.

One extra AiraBella unit was mounted in the flexible air duct, prior to discharging the air to the outside for environmental health and safety purposes.

Test Organisms

Four different organisms were tested: a bacterium (*E. coli*) and three different fungus spores (Table 1). The selection of the mold was made based on the frequency of occurrence in HVAC systems). The organisms were cultivated according to the methods recommended by ATCC. Plates with *Penicillium aragonense* and *Rhodotorula glutinis* formed a thick fungal mat and spores that would become airborne easily. This was not the case for *Cladosporium* sp. spores. Therefore, for *Cladosporium* sp. a spore suspension in water and Tween 80 (Fisher Scientific, Pittsburgh, PA) was aerosolized using the cost mister. *E. coli* was cultivated in LB medium using standard methods, harvested by centrifugation and resuspended in 9% NaCl solution prior to aerosolization using the cost mister. Because of the different methods of injection, the inlet concentration of the different organisms differed: it was from 16,000 to 160,000 CFU m^{-3} for *E coli*, 200 to 26,000 for *P. aragonense*, 5000, to 45,000 for *R. glutinis*, and 100 to 350 for *Cladosporium sp.*

Table 2. Characteristics of the test organisms

Organism	Source	Class	Method of injection	Remark
Escherichia coli, type W3110 (wild type)	Gift of Prof. W. Chen, UCR	Bacterium	Cold mist vaporizer of the organism	Good model test organism
Penicillium aragonense	ATTC #42228	Fungus	Entrain spores directly from Petri dishes	Isolated from air in Spain. *Penicillium sp.* spores are common air biocontaminants (reportedly in 91% of homes).[a]
Rhodotorula glutinis	ATCC #32765	Fungus	Entrain spores directly from Petri dishes	*Isolated from soil in Japan. Rhodotorula sp.* spores are common air biocontaminants (reportedly in 12% of homes).[a]
Cladosporium sp.	ATCC #32720	Fungus	Cold mist vaporizer	Isolated from air flow in air conditioner, Maryland. *Cladosporium sp.* spores are extremely common air biocontaminants (reportedly in 100% of homes).[a]

[a] Source: US-EPA 1991

Analytical Techniques

The concentration of organisms or spores in the air was determined in the influent and effluent air by filtering a known volume of air through sterile 0.22 µm pore filters (hydrophilic type, Millipore). All handling of samples followed aseptic procedures. The two sampling ports were located in the center of the duct, at 0.9 m prior to the UV section and 0.8 cm after the end of the UV section, for the before UV and after UV ports, respectively. Isokinetic (±10%) sampling of the air was accomplished by adjusting the sampling flowrate and the diameter of custom made interchangeable orifices located at the tip of the sampling probes in order to match the air velocity in the wind tunnel. Note that because of the significant reduction in viable counts before and after UV exposure, a different sampling time was sometimes used at the two sampling ports. For counting of viable organisms, the filters were transferred aseptically onto a Petri dish with the appropriate culture medium and agar, and colony forming units (CFUs) were counted after incubating the plates for 12 h to 5 days depending on the species undergoing testing. The filters were hydrophilic, so that when placed with the microorganism side facing up, nutrients would diffuse through the filters and enable viable organisms to grow. Analyzes were done at least in triplicate, and all analytical devices were sterilized between experiments. Several quality controls were conducted to ensure the representativeness of the results. They revealed that outside contamination either through the HEPA filter, or during sampling was virtually nil and that when the UV unit was not turned on, inlet and outlet samples had the same level of biocontaminants. Also, controls showed that there was no radial gradient in biocontamination, thus that sampling at one point in the cross the section of the duct was representative of the hole cross section.

Temperature was measured at 5 different locations in the wind tunnel using calibrated digital thermometers (Fisher Scientific, Pittsburgh, PA). Unless otherwise noted, the temperature during the experiment was 20 to 22 ^{o}C, and was uniform across the test bench. Relative humidity was measured using a thermo-hygrometer placed behind the second sampling port. The airflow was measured using an vane anemometer placed 0.2 m before the end of the actual wind tunnel.

RESULTS AND DISCUSSION

Disinfection of Model Biocontaminants

Results for disinfection tests are in plotted in Figure 2. Overall, the results show that *E. coli* disinfection is very efficient, with more than 98% of the organisms killed under all test conditions (Figure 2a). As expected disinfection was more effective with two UV lamps on than with only one, and kill ratio decreased with increasing the air flow rate. The data for disinfection of *P. aragonense* spores are presented in Figure 2b. Some scattering between experiments is visible, but the standard deviations within one set of experimental conditions is quite reasonable (usually about 5-10%). Although the inlet bioaerosol concentration should theoretically not influence the killing ratio, it is possible that some of the scattering (e.g., 1 vs 2 lamps, or different flowrates) is due to large changes in the inlet bioaerosol concentration. The latter were caused by the mechanism of bioaerosol production (plates with fungus and spores positioned in the air stream and spore allowed to naturally become airborne) which was largely depending on the airflow rate and on the time into the experiment.

The results for the disinfection of *R. glutinis* are reported in Figure 2c. The reduction ranged from 50 to 65%, in all cases, which is slightly better than for the *Penicillium sp.* and much lower than for *E. coli*. Examination of Figure 2c reveals that disinfection of *R. glutinis* was not greatly influenced by the airflow rate, which is unexpected. In a similar manner, the data for disinfection of the *Cladosporium sp.* spores are presented in Figure 2d. A reasonable disinfection rate of 65 to 75% is observed, depending on the experiment.

As mentioned, there seemed to be a low sensitivity to the airflow rate, which is counterintuitive. A rough evaluation using an exponential decay as in Equation 1 reveals that if the kill rate is 50%, doubling the flow would result in a kill ratio of 29%. Or if the measured kill ratio is 80%, doubling the airflow would result in a kill ratio of 55%. Thus, the overall measured disinfection efficacy does not appear to always follow a simple exponential kinetics, however, in absence of a better relationship based on a detailed understanding of the actual disinfection process, Equation 1 was used for further modeling of the process and extrapolation to other disinfection scenarios.

$$N_t / N_o = \exp(-E_{eff} \times k \times t) \text{ (fractional removal or \%)} \qquad \text{(Eq. 1)}$$

Where N_t is number of germs at time t after sterilization (i.e., downstream, after UV) and N_o is the initial number of germs before exposure (i.e., upstream), E_{eff} is the effective radiation dose measured in J m^{-2}, k is the kill or death rate constant (unit is 1/time) specific to the microorganism and t is the exposure time. This relationship shows that the efficiency of a UV sterilizer depends on the total input power, on the exposure time and on the specific microorganism present in the indoor air. Thus Equation 1 can be modified for a given geometry and flow. In its simples form, lumping a number of parameters in Eq. 1, it is proposed to use the power of the UV bulb instead of the actual UV irradiation, and 1/air flow instead of the exposure time. In doing so, all conversion factors are lumped into the k value, which becomes specific for a given system. k still remains a quantitative measure of the susceptibility of the organism to UV, but its absolute value is system specific. This modified form of Eq. 1 will be used further in the paper to fit the data and extrapolate to different conditions.

Disinfection of the different test organisms at a given airflow rate (1100 cfm) is compared in Figure 3. The graph shows that bacteria (*E. coli*) are easily killed, while fungal spores are much more difficult to kill. *P. aragonense* spores were the most difficult to kill. The fact that spores are more resistant to UV radiation has been widely reported. One should however stress that because death induced by UV irradiation is an exponential process, there is a very large difference between the susceptibility of *E. coli*, and this of the other test organisms.

Figure 2. Percentage reduction of A) *E. coli* CFU, and viable spores of: B) *P. aragonense, C) R. glutinis, D) Cladosporium sp.* as a function of the airflow rate through the wind tunnel.

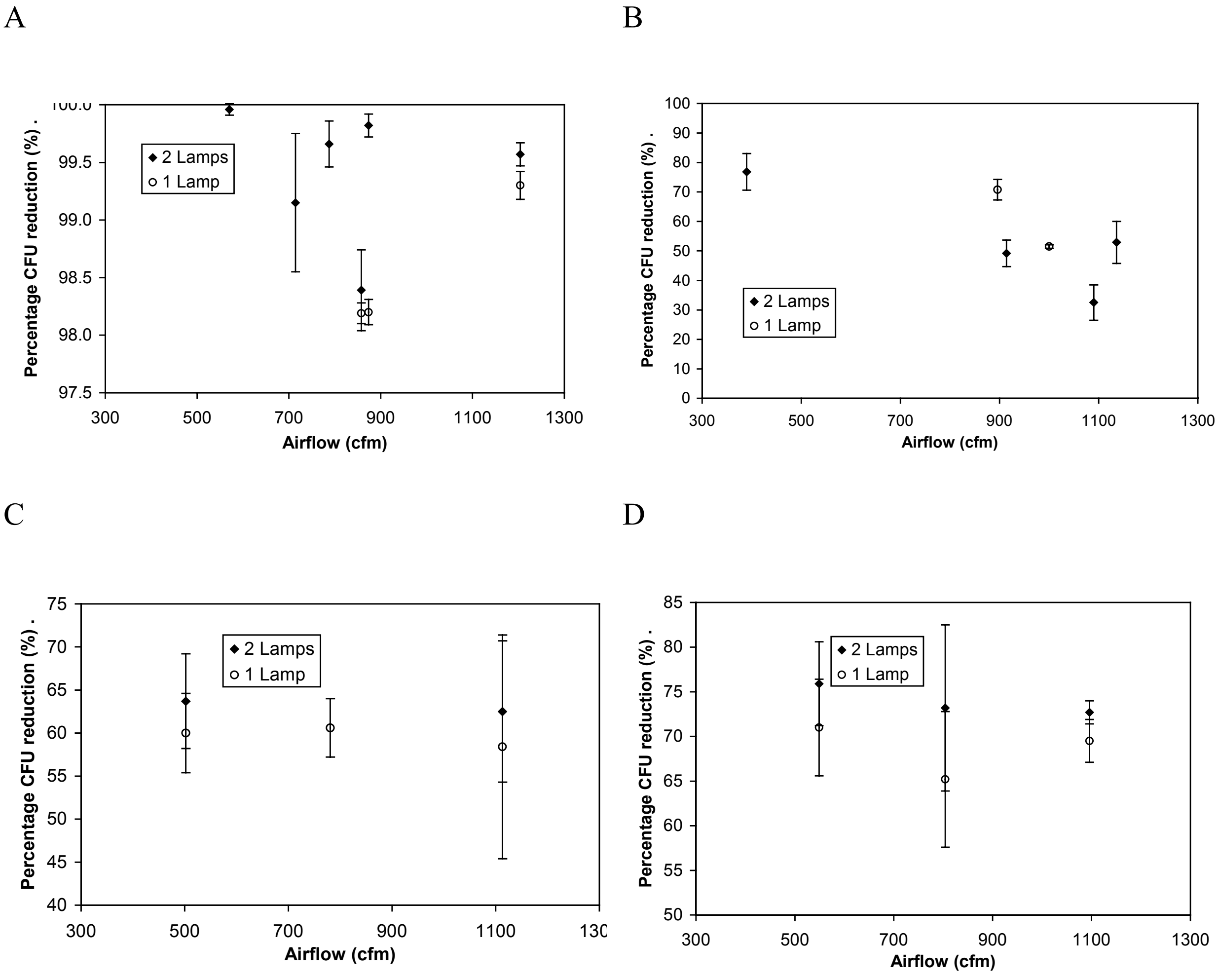
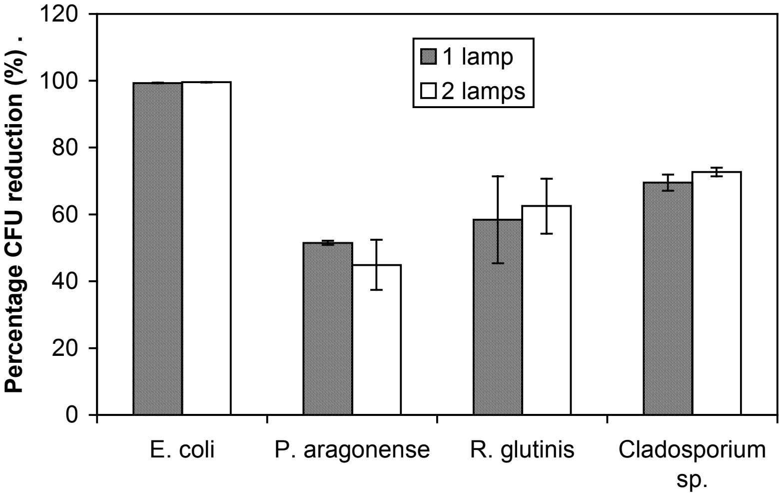


Figure 3 Comparison of disinfection efficacy for the different test organisms at a target flowrate of 1100 cfm.



In order to design UV disinfection systems, some basic model is needed. Equation 1 was initially developed for organisms exposed to a dose E_{eff} of UV radiation, for a time t and it needs to be adapted for in duct disinfection. In the wind tunnel, the average velocity of a contaminant is this of the bulk flow and it can be calculated by dividing the airflow rate by the cross section of the wind tunnel. The duration of the exposure to the UV depends on the length of the section in which there will be UV radiation present. In the absence of reliable UV distribution map, one can assume a unit length for which the organism will be exposed to UV and the duration of the UV irradiation (t) will be inverse proportional to the bulk air velocity. The irradiation is also unknown. The unit is watts/m^2. We used the power of the UV bulbs (18 watts per bulb on) for E. In doing so, we assumed a homogenous UV distribution and exposure time, which we know are not correct on an absolute scale, but it is acceptable in the absence of a detailed UV distribution map. The constant k, specific to the test organism is then fitted to minimize the residuals between the experimental and the modeled values. It should be noted here, that 1) Because of the form of Equation 1, a systematic error on either E or t has no consequence on the value of the residuals since k is fitted. It will however greatly affect the value of k. 2) Because of the approximations made above, the value of k that is obtained can not be compared to other published values of death rate constants. It can however be used in designing wind tunnels similar to the one that was designed and tested, or it can be compared to other organisms tested in the same system. 3) Because of the form of Equation 1, the model goes asymptotically to 100% killed when the airflow goes to zero.

Examination of Figures 4-7 reveals that the quality of the fit is average. The probable reason for this is the oversimplification of the UV disinfection process and the low degree of freedom that the model equation gives. Indeed, the model constraints are relatively stringent and do not allow for much variations. The model curves all have to go through the point <0 cfm; 100 kill ratio>, while following an exponential decrease. In absence of a detailed UV distribution map and computational fluid dynamics, it would be extremely difficult to develop a more detailed model without making excessive speculations. It is however possible to use the simple model for design with the understanding that uncertainties will remain.

Figure 4. Comparison of experimental data and modeled data for *E. coli*. (Note the model was fitted on the data with two lamps and used to predict the data with one lamp).

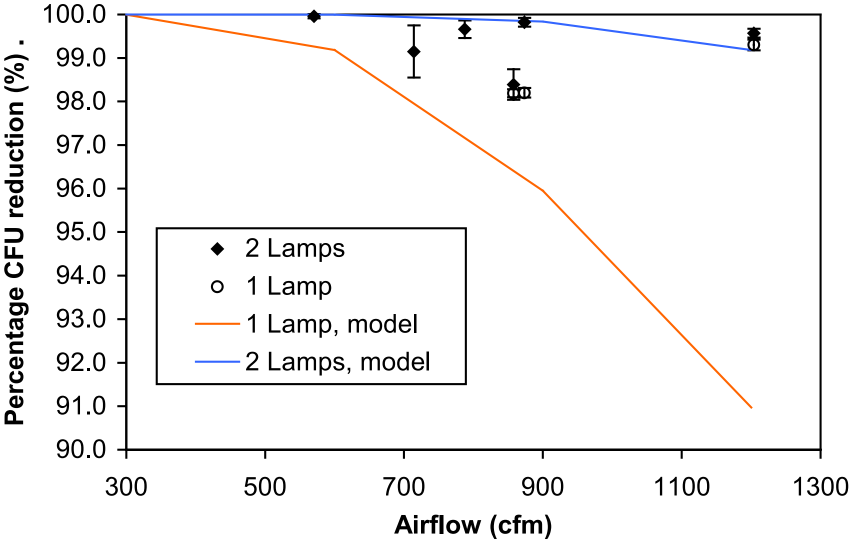


Figure 5. Comparison of experimental data and modeled data for *P. aragonense*. Data for one and two lamps were fitted together to obtain the best fit.

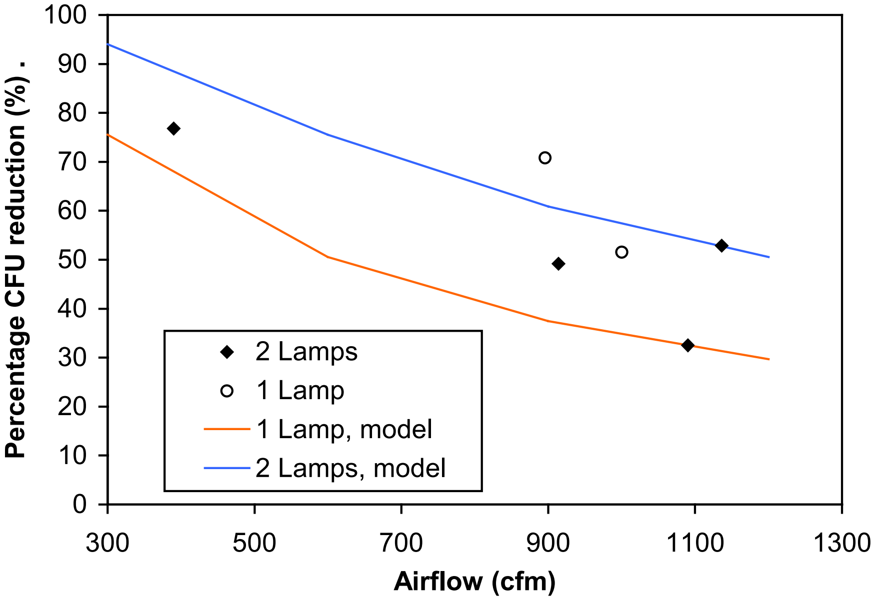


Figure 6. Comparison of experimental data and modeled data for *R. glutinis*. Data for one and two lamps were fitted together to obtain the best fit.

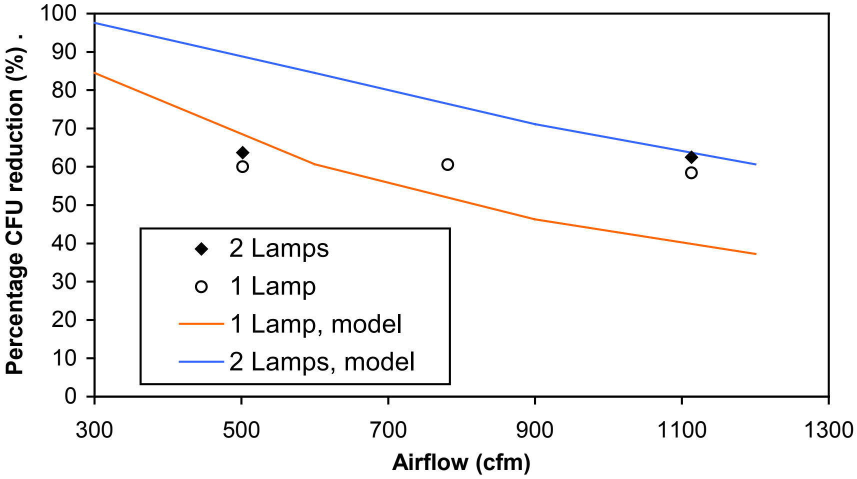
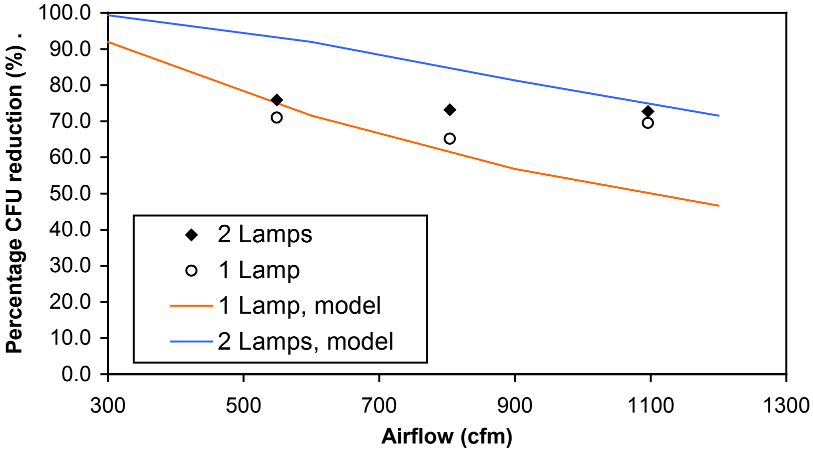


Figure 7. Comparison of experimental data and modeled data for *Cladosporium sp.* Data for one and two lamps were fitted together to obtain the best fit.



One possible application of the disinfection parameters and kinetics is the evaluation indoor air quality of buildings or houses under given scenarios. For this, two approaches are again possible: a complex description of the indoor aerodynamics and complex modeling e.g. using computational fluid dynamics, or a simple approach avoiding to seek a detailed description of complex non-ideal phenomena. The latter approach was chosen. Figure 8 shows the basic model structure. In order to establish the model equations, the following assumptions were made:

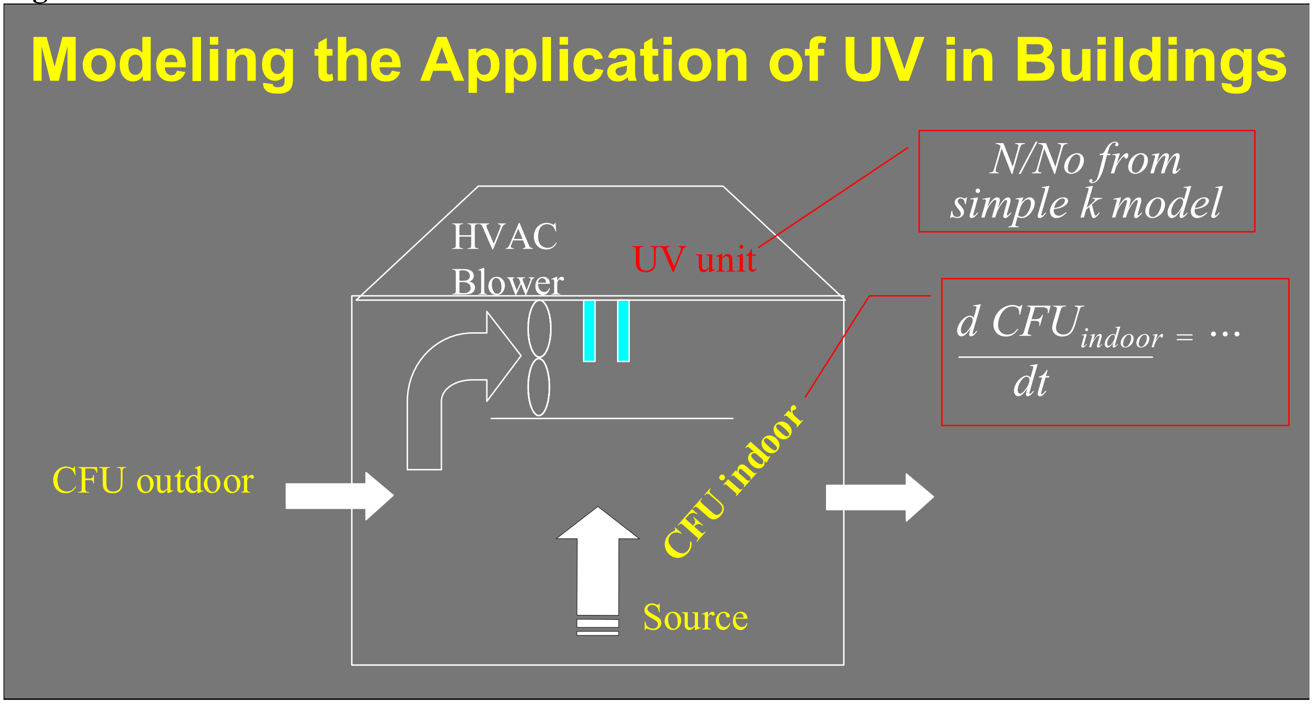
- The air in the building is assumed to be ideally mixed, so that the concentration of the biocontaminant is homogenous.
- Biocontaminant disinfection is assumed to follow the kinetics of Equation 1.
- All biocontaminants are lumped into a single biocontaminant for which the concentration in the indoor air is calculated. This means that only the contaminant of greatest interest, or this with the lowest susceptibility to UV is followed. Note that if there are several biocontaminants of interest, the model can be run several times with the different k and biocontaminant concentration values.
- The model equation is written in a dynamic manner so that evolution of indoor air quality over time can be modeled.
- For the simulation of indoor air quality in buildings or households, the model includes a constant source term inside the building, which is lumped into a single term. The model also includes a constant intake term for the outside air influx contribution.
- For bioterrorism protection, the model is modified to include a (timed) massive influx of a biocontaminant such as it would occur for crop-dusting of the biocontaminant or if a sudden spike of biocontaminant was injected into the building's air intake. Also the background term and indoor source are set to zero, since only the bioterrorism agent is simulated. Finally, the model includes calculation of the number of spores or CFU an average human would inhale, so that an assessment of the degree of control can be made on the basis of set target for human exposure.

Under these circumstances, the model equation for the concentration of biocontaminant inside the house or building becomes:

$$\text{VOLUME HOUSE} \times d(\text{CFU}_{\text{indoor}})/dt = \text{FRESH AIR FLOW} \times (\text{OUTDOOR} - \text{INDOOR CONCENTRATION}) + \text{SOURCE} - \text{UV DISINFECTION} \quad \text{(Eq. 2)}$$

in which the term UV DISINFECTION is calculated by Equation 1, with kill rate constants based on the experiments presented above. The model equations are solved numerically using a stiff algorithm.

Figure 8. Schematic of the model structure.



Modeling the Application of UV in Buildings

N/No from simple k model

$$\frac{d\,CFU_{indoor}}{dt} = \cdots$$

Figure 9 shows results of typical simulations. At a given time (here 10 min), the UV is turned on, and the improvement in indoor air quality is simulated. In Figure 9, the two extreme cases of UV susceptibility are plotted. For these, the best fit k values of *E. coli* and *Penicillium* spores were taken (see Figures 4-5). It can be seen that the indoor biocontamination drops very quickly after the UV is turned on, and that the improvement depends on the susceptibility of the organisms to UV. Repeating such simulation for different conditions allows to determine the sensitivity of the process to given parameters, such as the airflow of the HVAC blower and the UV power as in Figure 10. In this case, the pattern can be explained as follows. If the air flow is lower than 1500 cfm and UV power is more than 36 W of UV power, the single pass disinfection is virtually 100%. This means that increasing UV power would not result in any improvement, but that increasing the flow of the HVAC blower would have a major beneficial effect on the biocontaminant concentration , by increasing the number of passes through the UV disinfection unit. Experimental validation of these predictions is warranted.

Figure 9. Simulation of the application of UV air disinfection to a household. Parameters: 3000 sqft surface × 8 ft high house, 1500 cfm HVAC blower, outside air 1000 CFU/m^3, 200 cfm fresh air, significant indoor generation, UV = two 18 W bulbs. The k values considered range from easy to difficult to kill. (Note that k values can not be directly compared to other studies because of their units).

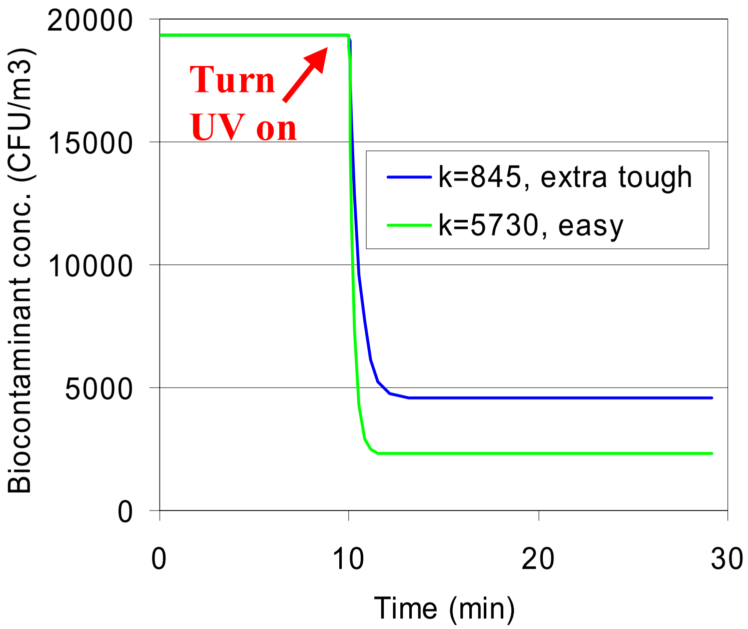
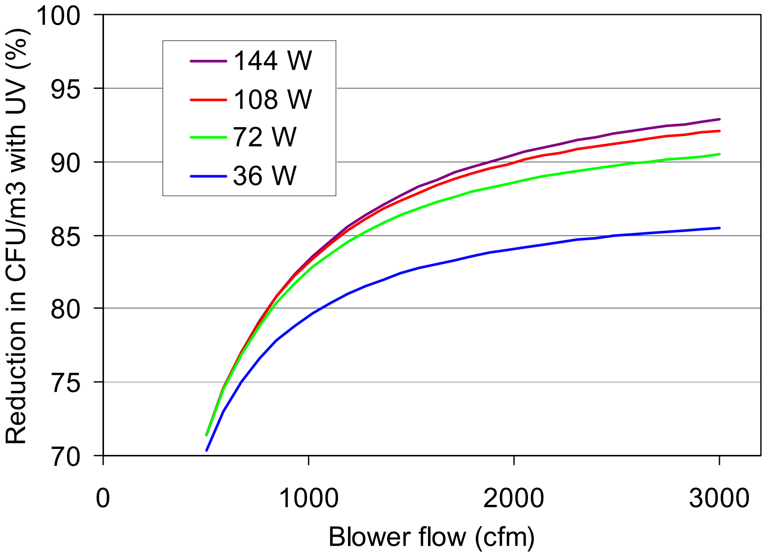


Figure 10. Sensitivity o UV air disinfection is a household. The reduction in indoor biocontaminant concentration vs. no UV is plotted. Parameters as in Figure 9, except for k = 1500 (=*Cladosporium sp.*)

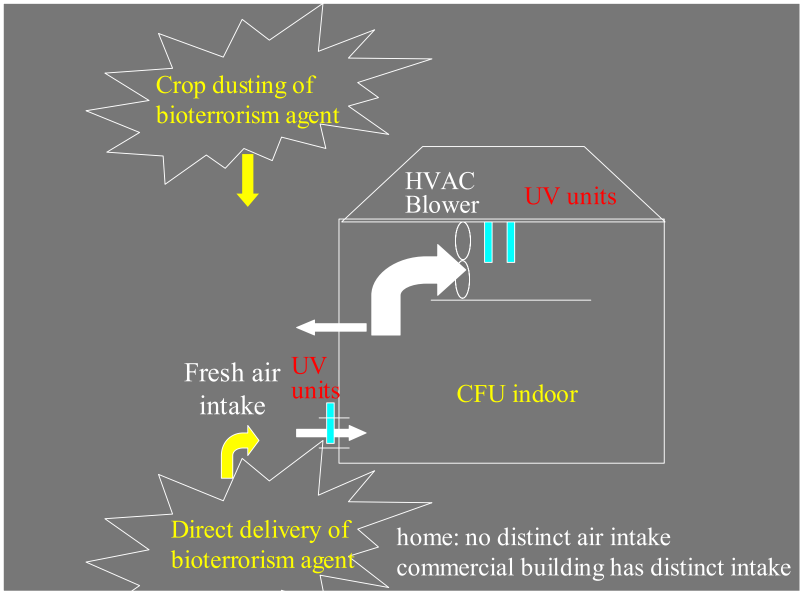


The simple modeling approach can be applied to the evaluation of the effect of UV disinfection in the event of a bioterrorism attack. The basic model structure to simulate such attack is shown in Figure 11. In defining the conditions for the simulation, there are significant challenges:

- The magnitude (i.e., biocontaminant concentration and release pattern) of a potential attack is unknown
- The value of UV susceptibility (k value) of the bioterrorism agent is unknown.
- Human susceptibility to biocontamination varies greatly from one individual to the other.
- A simple model would not capture the complex phenomena occurring in complex building air dynamics.

Still, simple modeling can illustrate the possibilities for UV to achieve a desired level of control, and optimize both the location of the UV units, as well as the UV power required. For the selection of the k value, a conservative approach is recommended, although it is known that viruses are very sensitive to UV. Here, we simulate an attack with *Bacillus anthracis* spores (anthrax), and by relative comparison with other studies (see e.g., Kowalski, 2002 and references therein), the k value of *Penicillium* spores, the most difficult organism to kill we tested, was taken. It is a conservative approach. For the simulation, a very rough estimate was made for the released amount of bioterrorism agent, and concentration vs. time pattern in the outdoor, based on the airplane crop dusting flows and volume, and assuming an exponential decrease of the pathogen concentration over time after the initial exposure. These are of course very crude approximation. Little information is publicly available on these topics.

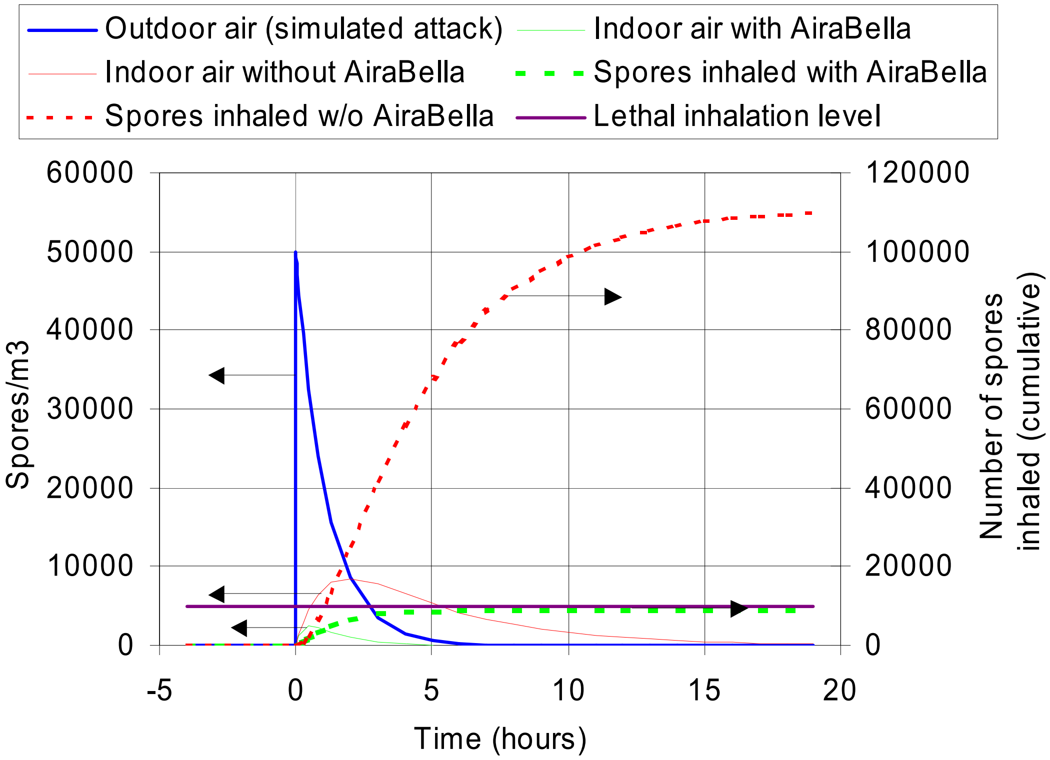
Figure 11. Basic model schematic for simulation of a bioterrorism attack.



Results of the degree of protection achieved using UV disinfection in a single family home are shown in Figure 12. Here, it is important to stress than the AC blower needs to remain on 100% of the time, which is typically not the case in family homes. Figure 12 illustrates that while the outdoor air reaches dangerously high levels, the indoor concentration of biocontaminant is reduced significantly. The amount of spores inhaled in a house without UV protection are well over lethal levels, while those in the house equipped with UV are exposed to doses just below the average lethal level.

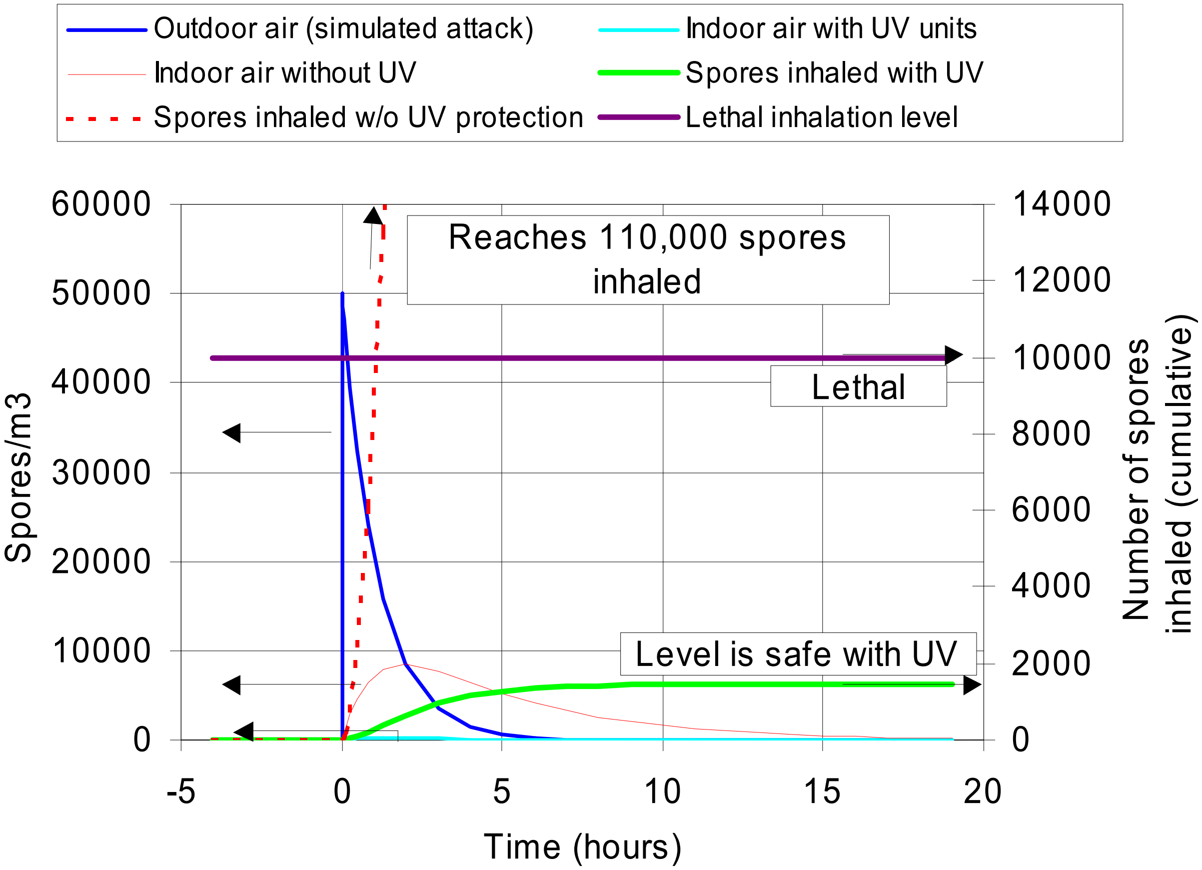
Part of the challenge in controlling indoor air quality in a family home, is the fact that personal homes have many points of fresh air entry (windows, leaks, doors, etc.). In the event of poor outside air quality or of an attack, this contaminated outside air will be homogenously distributed in the house, prior to treatment by the UV. That makes treatment highly dependent on these fugitive infiltration of outside air and on the flow of the HAC blower.

Figure 12. Simulation of the application of UV air disinfection to a household. Parameters: 3000 sqft surface × 8 ft high house, 2000 cfm HVAC blower, outside air 100 cfm (concentration of spores see blue line), 72 W UV bulbs. Breathing rate, 2 m^3 h^{-1} per person. k used is this of *Penicillium* spores.



In the event of a commercial building, a much better control on the fresh air flow and air quality is possible. The results of simulations are shown in Figure 13, for the same crop dusting of anthrax as in Figure 12. A much greater protection of the building's occupants is achieved, with the number of spores inhaled not exceeding 1800, i.e., markedly lower than the lethal level. Several simulations of the scenario of Figure 13 revealed both the potential and the limitations of the simple modeling approach. It was assumed that 216 W of UV power would be used and the effect of the location of the UV lamps was studied. The simulations revealed that the UV power would be best concentrated on the fresh air intake, instead of in the HVAC return air. In doing so, one controls the biocontaminant before it enters the building, and poses a risk to the occupants.

Figure 13. Simulation of the application of UV air disinfection to commercial building. Parameters: 20,000 sqft surface × 8 ft high house, 20,000 cfm HVAC blower, outside air 1000 cfm (concentration of spores see blue line), 144 W UV in the fresh air intake, 72 W UV in the air recycles. Breathing rate, 2 m^3 h^{-1} per person. k used is this of *Penicillium* spores.



CONCLUSIONS

The field of UV air disinfection is rapidly expanding. The results presented and discussed in this paper showed that UV disinfection can be extremely effective. The modeling exercise revealed that several challenges exist in accurately modeling the disinfection kinetics, and the deployment of UV in HVAC systems. However, with a few approximations, meaningful information was obtained on the application of germicidal UV for indoor air quality. Simulation of Homeland Security issues helped in understanding what parameters were most important in developing strategies to protect buildings from attacks, and maximizing the benefits of UV, while minimizing the energy and equipment costs.

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