LIFE-CYCLE COST SIMULATION OF IN-DUCT ULTRAVIOLET GERMICIDAL IRRADIATION SYSTEMS

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ABSTRACT

Ultraviolet Germicidal Irradiation (UVGI) systems use 254 nm UVC radiation to inactivate microorganisms in the air and on surfaces. In-duct UVGI systems are installed in air-handling units or air distribution systems to inactivate microorganisms "on the fly" and on surfaces. The literature contains few investigations of the economic performance of UVGI. This study presents a simulation-based life-cycle cost analysis of in-duct UVGI in a hypothetical office building served by VAV systems. Three scenarios are considered: UVGI in the mixed air stream upstream of the cooling coil, UVGI downstream of the coil, and equivalent enhanced filtration without UVGI. The upstream location results in lower first and operating cost for UVGI due to a more favorable thermal environment for UV lamps. UVGI in either location is much lower in annualized cost than equivalent enhanced filtration. The methodology presented could serve as a model for an improved design process.

KEYWORDS

Ultraviolet germicidal irradiation, UVGI, Life-cycle cost analysis, LCC, Airborne contaminant control, Indoor air quality.

INTRODUCTION

Transmission of respiratory diseases by airborne pathogens is one of the major problems of indoor air quality (IAQ). Heating, ventilation and air-conditioning (HVAC) systems may participate in distribution and control of infectious microorganisms. Dried residues of droplets generated by talking, coughing and sneezing can be suspended in the air for several hours, entrained into HVAC ductwork, and distributed throughout a building (Sehulster et al., 2004). However, these entrained particles may be efficiently removed or inactivated by filters and other air cleaners.

Ultraviolet germicidal irradiation (UVGI) is an alternative to high efficiency particulate filtration for controlling airborne microorganisms. UVGI systems typically use 254 nm UVC radiation produced by low pressure mercury vapor lamps to disrupt the DNA or RNA of microbes, thus impairing their ability to replicate. (Noakes et al., 2004, Philips, 2006).

The output of low pressure mercury vapor lamps is quite sensitive to ambient temperature and air velocity ("wind chill" effect) and also decreases (depreciates) as operating hours accumulate. The ambient condition response of a commonly used lamp (Philips TUV PL-L 60W HO) oriented in cross flow is shown in Figure 1. Contours in Figure 1 indicate UVC output relative to the maximum produced by the lamp under ideal operating conditions. A typical depreciation curve is shown in Figure 2.

The survival fraction S of a microbial population exposed to germicidal radiation at a fluence rate I [$\mu W/cm^2$] for a time t is expressed by the Chick-Watson disinfection equation:

$$S = \frac{N_t}{N_o} = e^{-k(It)} \tag{1}$$

in which the factor k [$cm^2/\mu W\text{-}s$] represents the resistance of the species of interest. Higher values of k reflect greater susceptibility. The product It is the UVC dose. Based on Equation 1, the design dose $(It)_{Design}$ for a given microbe is:

$$(It)_{design} = \frac{\ln(S_{design})}{-k} \tag{2}$$

Dose varies with both lamp output and exposure time. In general,

$$\frac{It}{(It)_{design}} = \left(\frac{LampOutput}{LampOutput_{design}}\right)\left(\frac{V_{design}}{V}\right) \tag{4}$$

The single pass UVGI inactivation efficiency is:

$$\eta_{UVGI} = 1 - S = 1 - e^{-k(It)} \tag{3}$$

Air temperature and velocity may vary over a wide range in an HVAC system, causing substantial changes in both I and t that are rarely accounted for in system design and analysis in a rigorous way.

In HVAC systems, UVGI for air treatment is generally installed in the supply air stream of an air-handling unit (AHU) in a position that may also irradiate cooling coil, filter surfaces and the condensate pan to control other potential microbial growth problems. Requirements for air treatment typically control the sizing of these "in-duct" UVGI systems, due to the short time (as little as 0.25s) available to deliver an inactivating dose.

Depending upon the practices of a given manufacturer, the installation location may be upstream of the cooling coil (identified as “mixed air” or MA for the purposes of this discussion) or downstream of the cooling coil (“supply air” or SA). The location of the UVGI device relative to the cooling coil is significant, as it greatly changes the temperature of the lamp environment. The shaded boxes in Figure 1 illustrate typical differences between temperature and velocity ranges encountered in these two locations and the impact on the range of lamp output.

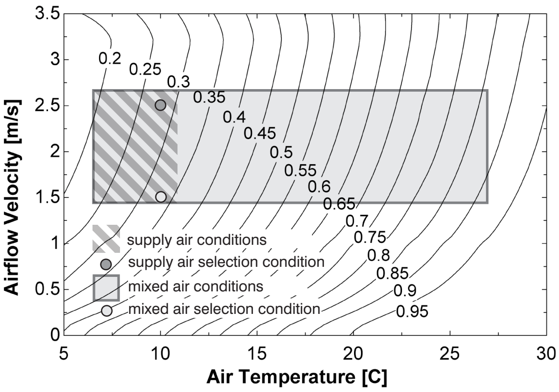

Figure 1. Relative UVC output contours for Philips TUV PL-L 60W HO lamp in crossflow (Lau, et al., 2009)

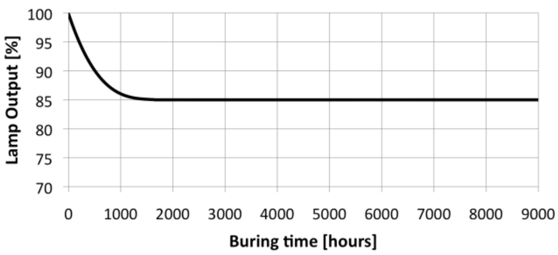

Figure 2. Typical germicidal lamp depreciation curve (adapted from Philips, 2006)

UVGI Economics

A primary desired benefit of any air treatment technology is (at a minimum) prevention of avoidable adverse impacts on health, productivity, and comfort. Fisk (2002) has quantified these benefits on the national scale for the U.S. in terms of annual health care, sick leave, and productivity economic impacts. It is not a simple matter to translate these estimates into benefits associated with specific measures taken in a particular building, although attempts have been made to do so. For example, Fisk, et al. (2005) applied the Wells-Riley equation to an analysis of the benefits of air-side economizer operation. Whether on the national scale or the building scale, such analysis generally show a very large benefit for increased indoor air quality.

The principal costs of an air treatment technology are its initial capital cost and its operation and maintenance costs. These costs are affected by both the sizing of the system and how it is operated. For UVGI systems, operation and maintenance costs include the cost of electricity to operate the lamps, increased cooling load (offset by decreased heating load), and lamp replacement. For a given system, these costs can be estimated reasonably well with the aid of simulation.

While the literature contains numerous theoretical and experimental studies on the effectiveness of UVGI systems, discussions of the cost effectiveness of UVGI based on standard economic analysis techniques are lacking. Better understanding of costs and benefits associated with the use of UVGI, or any air treatment technology would support its appropriate application and might also lead to improvements in design practice. A rigorous economic analysis of a UVGI system requires simulation of both its performance relative to design air quality control targets and its annual energy use.

This study combines results of hourly annual simulations described in a companion paper (Bahnfleth, et al., 2009) with economic analysis to estimate the life-cycle cost of in-duct UVGI in a representative building. The primary objectives of the study are to provide an example of UVGI economics and to illustrate basic components of a simulation-based design procedure for UVGI systems.

METHODOLOGY

Building and HVAC Systems

Parametric simulations were performed for a hypothetical four-storey office building located in New York, NY. The building was conditioned by variable air volume (VAV) systems. Each floor of 2,378 m^2 (25,600 ft^2) was served by an independent AHU capable of delivering a supply air flow of 8m^3/s (17,000 cfm) and constant ventilation air flow of 1.8 m^3/s (3837 cfm), i.e., 22.5% of design supply air flow. The design supply air temperature was 10°C (50°F) and air velocity at design flow rate was assumed to be 2.5 m/s (500 fpm). The base system was assumed to have MERV 6 particulate filters (ASHRAE, 2007). For the purposes of this study, only one system from a middle floor was studied in detail.

A UVGI device was located in the AHU either downstream of the cooling coil (“SA”) or upstream of the cooling coil (“MA”). Figure 3 shows the general arrangement of a typical system. The downstream location favored by some permits simultaneous air treatment and irradiation of the condensate pan, but it is apparent from consideration of Figure 1 that the, on average, colder environment downstream of the coil also results in lower lamp output. HVAC system and UVGI operation were assumed to be continuous, i.e., 8760 hrs/yr.

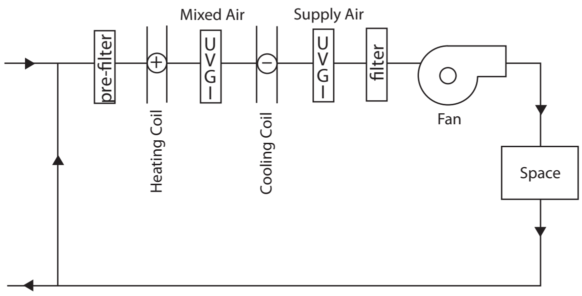

Figure 3. Study building HVAC system schematic showing UVGI location options upstream and downstream of cooling coil

Building energy simulation software – the eQUEST implementation of DOE2 (Hirsch, 2009) - was used to perform an 8760-hour whole building energy analysis and to provide hourly data such as flow rate (Q) and temperature (T) of the air stream. Data from the annual energy solution were used to calculate lamp output in a custom MATLAB program (MathWorks, 2009).

UVGI Systems

The two common UVGI locations noted earlier, upstream of the cooling coil, and downstream of the cooling coil, were both simulated so that the impact of ambient conditions on system economics could be compared. In order to properly select a UVGI system, the designer must know the target k value and inactivation efficiency (which determines the design dose), the range of temperature and velocity at the installation location (which determines the design lamp output), and details of system geometry and material properties (which determine residence time and the irradiance distribution). For the purpose of determining residence time, a streamwise irradiated zone length of 75 cm (30 inches) was assumed.

The arbitrarily chosen design microorganism for this study was *Staphylococcus aureus,* for which a conservative (more resistant) estimate of k is 0.0035 $cm^2/\mu J$ was used (Sharp, 1940). Values obtained by other investigators are as much as an order of magnitude larger. For purposes of particulate filtration, a diameter of 1 µm was used. Standard MERV 6 filters were assumed to have an efficiency of 15% for 1 µm particles.

Systems were sized for worst-case single pass *S. aureus* inactivation of 85% using the proprietary design software of the third author's company under temperature and velocity conditions identified as extreme for each location. Typical AHU installation geometry and material properties were assumed. Lamp characteristics were those of Philips model TUV PL-L 60W HO lamps in cross flow. Lamp ambient condition response and depreciation characteristics were assumed to be as shown in Figures 1 (Lau, et al. 2009) and 2 (Philips 2006), respectively.

Study Cases

Three system configurations were modelled:

- Base HVAC system (minimum outside air + MERV 6 filtration) + UVGI downstream of the cooling coil
- Base HVAC system + UVGI upstream of the cooling coil
- Base HVAC system + higher efficiency final filter comparable in effect to the base system + UVGI.

The first two cases afford the opportunity to investigate the effect of wind chill on sizing and operating cost. The third case provides a comparison between UVGI and the most likely alternative technology, with the comparison being done on the basis of (to the extent possible) equivalent performance. The latter comparison is particularly important, as indoor air quality (IAQ) equipment comparisons are frequently made by looking at a single technology and comparing well-defined costs with nebulously or undefined benefits. This is not a fair comparison unless good IAQ is viewed as optional.

Energy Analysis

A UVGI air disinfection system affects the energy use of a building in at least four ways: direct energy consumption for lamp operation, increased cooling energy consumption, decreased heating energy consumption, and changes in fan power consumption due to changes in supply air temperature and additional pressure drop caused by the UVGI components in the moving air stream.

The power consumption of lamps was assumed to be constant at the value determined by the manufacturer's sizing calculations. Heating and cooling load impacts of lamps were approximated by making small increases in the sensible heat load of the spaces served by the system. Ideally, this heat would have been added at the actual point of generation in the AHU, but this could not be done due to limitations of the modeling software.

Foarde et al. (2006) tested in-duct UVGI equipment provided by eight manufacturers and found that the pressure drop across most systems was less than 8 Pa (0.032"w.g.). Given that this additional peak pressure loss is perhaps 1-2% of the total static pressure of a typical supply fan, associated differences in fan power were neglected as negligible.

Economic Analysis

The economic performance of the studied systems was evaluated in terms of 15-year constant-dollar life-cycle cost (LCC) using economic parameters representative of current conditions in the U.S. These included a 3% real discount rate (NIST, 2008) and a 2008 average electric cost of $0.10/kWh (EIA, 2008). Energy cost for subsequent years was adjusted using the U.S. government's projected price indices which predicted real future rates (i.e., measured in 2008 dollars) to range from 89 to 98% of the baseline year rate.

The installed cost of UVGI equipment was estimated at \$10 per W of input power. Annual maintenance cost was assumed to be \$1 per input W based on annual lamp replacement. These figures are budget-level numbers that do not reflect premiums or discounts that might result from project-specific conditions and competition.

Comparison of Filtration and UVGI

A filter removes particles from a treated air stream while UVGI inactivates viable microorganisms without removing them and has little or no effect on non-viable aerosols. In addition, the efficiency of a UVGI device can vary over a much wider range due to the effects of operating conditions than a typical particulate filter. Consequently, a direct equivalence between the two does not exist. However, the single-pass inactivation efficiency of a UVGI device is conceptually equivalent to the grade efficiency of a particulate filter for a particular microorganism of interest. This limited definition of an “equivalent filter” can be used as the basis for an energy and economic comparison between UVGI and particulate filtration by comparing UVGI performance to the performance of a system in which a filter of the same single pass efficiency for the microorganism of interest replaces UVGI.

For the assumed 1 μm diameter *S. aureus* aerosol assumed in this study, a MERV 12-13 filter would provide an 85% single-pass removal rate (Kowalski et al., 2002), analogous to the 85% single pass inactivation efficiency of the modelled UVGI system. MERV 12 filter characteristics were used in this study in the interest of a conservative (i.e., less favorable to UVGI) comparison.

Based on costs published by a number of on-line sources, the initial cost of a MERV 12 filter system was assumed to be \$1650 per m^2 (\$150/sq.ft.) of AHU cross-sectional area of the AHU, and a replacement cost of \$220/m^2 (\$20/sq.ft.). Manufacturers recommend that filters be changed every 3 months to a year. In this study, filters were assumed to be replaced every six months.

According to Schloss (2007), a typical MERV 12 filter will induce a design pressure drop of 250 Pa (1”w.g.). The additional pressure drop was added to the supply air path of building energy analysis model so its effect would be reflected in fan energy consumption.

Estimate of IAQ Benefit

Calculation of health benefits generally followed the method employed by Fisk, et al. (2005) in their analysis of economizer operation. In the present case, the objective was to relate inactivation of microorganisms by UVGI to reduced risk of infection via the Wells-Riley equation. In order to do so, it was necessary to calculate an equivalent ventilation rate to represent the effect of UVGI, i.e., the additional uncontaminated air flow that would result in the same reduction in supply air concentration.

The Wells-Riley equation relates risk of infection to the rate of emission of infectious particles and the rate of dilution by ventilation air:

$$P = 1 - \exp\left[-\frac{ipqt}{Q} \right] \quad (5)$$

where P is the proportion of new disease cases to the susceptible population, i is the number of infectors, p is their breathing rate, q is the rate of infectious particle emission per unit volume of respiration, and t is the duration of exposure of susceptible. Fisk, et al. utilize a modified form of Equation 5 in which they introduce the ventilation rate per unit volume ($Q/\not{V}$), i.e., the ventilation air change rate, represented here by the symbol α_v (n_v in the original):

$$P = 1 - \exp\left[-\frac{ipqt}{\not{V}} \Big/ \alpha_v \right] \quad (6)$$

The parameter α_v figures in estimates of relative risk as described later.

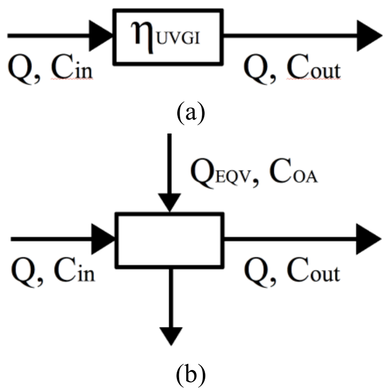

Figure 4. Analogy between UVGI air treatment and equivalent ventilation: (a) actual system, (b) equivalent ventilation analogy

Referring to Figure 4a, the effect of a UVGI system on an air stream containing a microbial contaminant can be described by its single-pass efficiency:

$$\frac{C_{out}}{C_{in}} = 1 - \eta_{UVGI} \quad (7)$$

If, instead, the incoming stream of contaminated air is diluted to the same leaving concentration by contaminant-free outdoor air at a rate Q_{EQV}, as in Figure 4b, it can be shown that

$$\frac{C_{out}}{C_{in}} = (1 - \frac{Q_{UVGI}}{Q}) \quad (8)$$

It is clear, therefore, that there is a direct analogy between ventilation and UVGI such that the use of UVGI with a single-pass efficiency on an airstream with flow rate Q is equivalent to dilution with an uncontaminated air flow Q_{EQV}. By analogy to Equation 6, there is also an equivalent UVGI ventilation rate per unit volume:

$$\alpha_{UVGI} = \frac{Q_{UVGI}}{V} \quad (9)$$

Equivalent ventilation and air change rates can likewise be derived for other removal mechanisms such as particulate filtration.

Fisk et al., (2005) present a relative risk model based on Equation 6 and note that the key proportionality it indicates is that

$$P \propto 1 / (\alpha_V + \alpha_f + \alpha_d) \quad (10)$$

From which they derive an estimate of relative risk of the following form:

$$RR = \frac{P_{UVGI}}{P_{ref}} = \frac{1/(\alpha_{UVGI} + \alpha_V + \alpha_f + \alpha_d)}{1/(\alpha_{V,ref} + \alpha_f + \alpha_d)} \quad (11)$$

Where subscripts $\alpha_{V,ref}$, α_f, and α_d, represent a reference ventilation air change rate and equivalent air change rates for particle filtration and deposition, respectively. Following Fisk, et al., the value of reduced sick leave was estimated to be \$200 per person-day, a baseline sick leave rate was assumed to be 2%, and occupant density 5 persons/93 m^2 (5 persons/1000 ft^2), and relative risk was calculated using Equation 11.

RESULTS

UVGI System Selection

According to Equation 1, the UVGI device must deliver a design dose of 542 μJ/cm^2 for the selected k and η_{UVGI} values. The nominal lamp capacity required to achieve this dose depends, as noted above, on a number of factors. These include the air temperature and velocity distributions to which lamps are exposed. In some cases, the worst case wind chill condition may be determined by inspection, but in some cases, simulation can help to identify a true worst case condition that is not self-evident.

Monthly lamp output distributions at the two UVGI locations obtained from calculations based on results of a preliminary energy simulation are shown in Figure 5. Results are presented in box and whisker diagram format. The line within the box indicates the median value of the entire sample, the ends of the box bound the quartiles above and below the median, and the ends of the whiskers indicate the limits of the data set. Asterisks denote outliers.

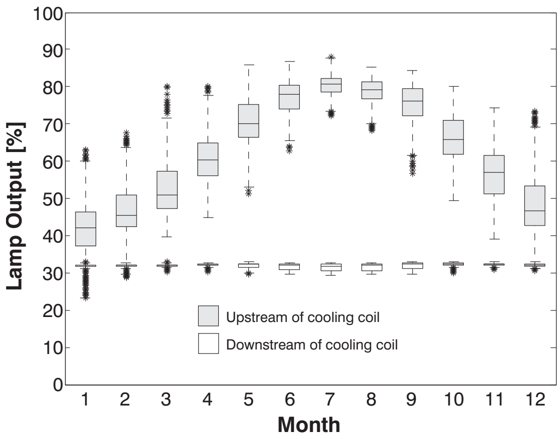

Figure 5 Monthly lamp output upstream (mixed air) and downstream (supply air) of cooling coil.

Lamp output was calculated using the model of Lau, et al. (2009) for every hourly air temperature-velocity pair from the energy simulation so that worst-case design conditions could be identified. Relative UVC output for the location downstream of the coil (supply air) was nearly constant over the entire year with a value slightly above 30% while median monthly output for the upstream location varied between roughly 40% and 80%, with the highest values in the summer and the lowest values in the winter.

The reasons for these differences can be seen in the relationship of lamp ambient condition zones and lamp output contours in Figure 1. The boxes superimposed on the lamp performance map are bounded by the high and low velocity and temperature values obtained from simulation at the two UVGI locations. All of the possible operating conditions of the downstream lamp are clustered in a low-efficiency part of the map while the upstream location extends, during summer operation, into a relatively high efficiency region.

Not all of the possible combinations of air velocity and temperature implied by each box in Figure 1 will occur. It is particularly important to note that at the mixed air location upstream of the cooling coil high air velocities and low temperatures will not occur at the same time because mixed air is coldest during the winter when cooling load, and therefore, VAV air flow is lowest. Temperature is consistently low at the supply air location downstream of the cooling coil, so the coincidence of low temperature and high velocity is to be expected. This is important information needed for the identification of a suitably, but not overly, conservative design condition.

With the aid of energy simulation results, it was possible to identify worst case conditions—those at which η_{UVGI} was lowest—more precisely. These upstream and downstream design points are shown on Figure 1.

Table 1 Design parameters at supply air and mixed air locations for 85% inactivation of S. aureus.

	Supply Air	Mixed Air
Temperature, ˚C (˚F)	10 (50)	10 (50)
Velocity, m/s (fpm)	2.5 (500)	1.5 (300)
Exposure time (s)	0.3	0.5
Lamp Output (%)	27.8	32.9
Irradiance (μW/cm^2)	6499	3295
Input power (W)	718	364

Table 1 summarizes the results of the sizing analysis. As can be seen from Figure 1, lamp output is more sensitive to temperature than air velocity within the range of ambient conditions, so the worst case sizing condition in both the upstream (mixed air) and downstream (supply air) locations occurred at minimum air temperature. Lamp output in the upstream location is only 18% greater than in the downstream location, but the required irradiance downstream is greater by almost a factor of two because of the effect of longer residence time at the lower flow rate of the upstream design condition.

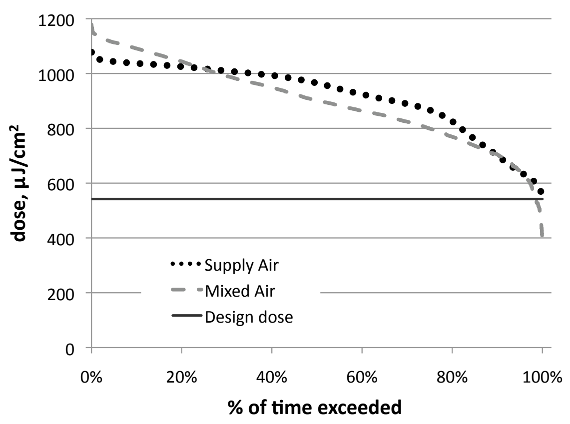

Figure 6. Duration curve of dose for supply air and mixed air UVGI locations.

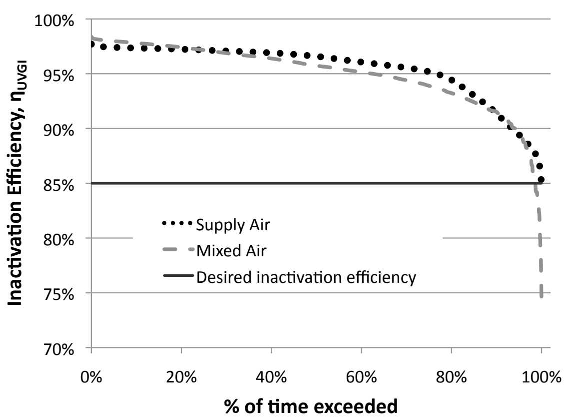

Figure 7. Duration curve of inactivation efficiency for supply air and mixed air UVGI locations.

Figures 6 and 7 show the annual distribution of dose and η_{UVGI} for *S. aureus* resulting from the selected systems. Both UVC dose and η_{UVGI} are well above design levels most of the time, suggesting that a somewhat less extreme design condition might be acceptable in some cases. Distributions in supply air and mixed air are somewhat different, but not drastically so, and the differences in η_{UVGI} are smaller than differences in dose.

Energy Use and Cost

Table 2 summarizes energy use and cost results. Over the course of a year, UVGI at the upstream location, with its higher average lamp efficiency, consumes roughly half the energy of UVGI at the downstream location. Annual energy cost for UVGI operation varies from \$0.10 – 0.20/m^2 (\$0.01 – 0.02/ft^2), which is small in comparison to the annual energy cost of a typical commercial building, which may be \$20/m^2 (\$2/ft^2) or more. Enhanced filtration equivalent to 85% efficient UVGI for *S. aureus,* on the other hand, is an order of magnitude more expensive to operate at over \$1/m^2 (\$0.10/ft^2). The base total energy consumption of the building predicted by modeling was 1.8 GWh, so UVGI added no more than 0.3% to the total energy consumption.

Table 2 Annual energy consumption and cost

Annual Energy Consumption	UVGI @ SA	UVGI @ MA	MERV 12 filtration
Power to lamps (kWh)	6290	3189	-
Cooling (kWh)	1175	575	9975
Fan (kWh)	400	200	17175
Heating-electric (kWh)	–3063	–1487	–506
Net (kWh)	4802	2477	26,644
kWh/m^2 (kWh/ft^2)	2 (0.2)	1 (0.1)	11 (1)
Cost (\$)	480	248	2664
\$/m^2	0.20	0.10	1.12
(\$/ft^2)	(0.019)	(0.010)	(0.104)

Life Cycle Cost

Annualized 15-year LCC results are shown in Table 3 as building totals and as costs per unit area. As in the case of energy costs, the total cost of UVGI upstream of the cooling coil in the mixed air stream is about half that of UVGI downstream of the coil in the supply air stream.

Life-cycle costs are closer to one another than energy costs because of differences in installation and maintenance (lamp replacement) costs. Over the 15 year lifetime of the system, UVGI installation and lamp replacement costs in this example are almost the same and both are greater by 50% than energy cost. In contrast, lifetime energy cost for MERV 12 filtration is the largest component of life cycle cost.

Table 3 Annualized life-cycle cost

a) Total cost [$] for study building

	UVGI in Supply Air	UVGI in Mixed Air	MERV 12 Filtration
Installation	601	305	429
Replacement	718	364	1359
Energy	444	229	2460
Total	**1763**	**898**	**4248**

b) Unit cost [$/m^2 ($/ft^2)]

	UVGI in Supply Air	UVGI in Mixed Air	MERV 12 Filtration
Installation	0.25 (0.024)	0.13 (0.012)	0.18 (0.017)
Replacement	0.30 (0.028)	0.15 (0.014)	0.57 (0.053)
Energy	0.19 (0.017)	0.10 (0.009)	1.04 (0.096)
Total	**0.74 (0.069)**	**0.38 (0.035)**	**1.79 (0.166)**

IAQ Benefit

Both UVGI and MERV 12 final filtration reduced relative risk of infection, according to the method of Fisk, et al. (2005), to 40 – 50% of baseline, as shown in Figure 8.

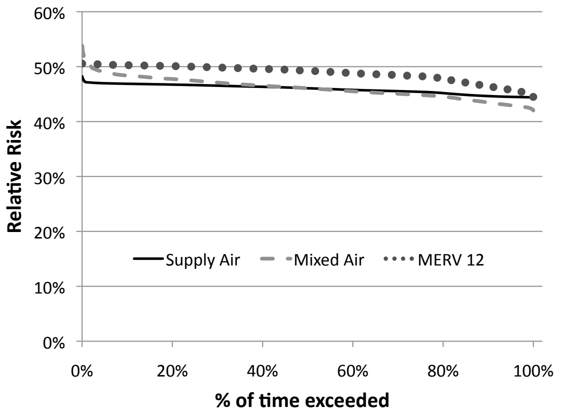

Figure 8. Duration curve of relative risk of infection for UVGI or MERV 12 filtration

The estimated annual benefit in economic terms is shown in Table 4. As noted previously, these predicted benefits are an order of magnitude larger than the cost of a UVGI system and also several times larger than the cost of enhanced filtration.

Table 4 Annual health benefit as a result of lower relative risk

Operation Scenario	Health Benefit $/m^2 ($/ft^2)	Health Benefit $/person
UVGI @ SA	40.4 (3.75)	750
UVGI @ MA	39.9 (3.71)	742
MERV 12 filtration	38.0 (3.53)	706

DISCUSSION

Engineering investment decisions are generally made on the basis of a cost-benefit analysis in which a clearly quantifiable outcome such as energy cost savings is compared to the cost of the system modifications required to achieve it. As has been noted, this approach is difficult to apply for general indoor air quality applications because of both the uncertainty of benefits and their huge magnitude when quantified.

The claimed economic benefits of better IAQ are so large that they would justify virtually any IAQ measure. For this reason, the cost-benefit analysis in this study was framed somewhat differently, i.e., in the form of a comparison between UVGI and an "equivalent" particulate filter enhancement. It should be noted that this equivalency is a partial one, particularly because of the selectivity of UVGI and the broad spectrum control afforded by filters.

The analysis presented in this paper is limited in many respects — geography, occupancy, HVAC system characteristics and operation, energy rates, economic analysis parameters, and others. Therefore, conclusions drawn from it should not be taken as definitive.

CONCLUSIONS

Based on the analysis summarized in this paper, the following conclusions can be drawn:

- Because of differences in air temperature upstream and downstream of a cooling coil, the sizing of UVGI systems intended to meet the same target η_{UVGI} and resulting annual energy and maintenance costs may be quite different. UVGI located upstream of the cooling coil was substantially more cost effective for air disinfection than UVGI downstream of the coil.
- Sizing methods employed by manufacturers, as exemplified by the approach used in this study, result in conservatively (not necessarily excessively) sized systems. It is possible that cost savings could be realized by a somewhat less extreme sizing.
- The annual energy cost of even an 8760 hour UVGI system is small relative to typical whole-building energy cost.
- UVGI can be significantly more cost effective than equivalent high efficiency filtration for microbial air contaminants.
- Predicted health benefits of UVGI and other air treatment technologies are large — so large that they overwhelm costs in a cost-benefit analysis.
- Simulation is a valuable tool for UVGI around which improved performance-based design procedures leading to more optimal solutions can be structured.

This study has sketched the fundamentals of an improved, simulation-based design methodology. That could lead to improved performance or better economics for UVGI systems. Further research to consider a broader range of parameters and further define a rational design process is warranted.

NOMENCLATURE

C	concentration of microorganism in space (#/m^3)
I	the effective (germicidal) irradiance received by the microorganism ($\mu W/cm^2$)
k	microorganism-specific rate constant ($cm^2/\mu W\text{-}s$)
N	size of a microbial population of the microorganism
P	proportion of new disease cases
Q	volume flow rate (m^3/s)
RR	relative risk
S	N_t / N_o, survival fraction of the microorganism
t	exposure time (s)
T	air temperature (˚C)
V	airflow velocity (m/s)
V̶	space volume (m^3)
α	air change per hour
η	efficiency (%)

Subscripts

d	deposition
design	design values
EQV	equivalent
f	filter
in	from upstream of the system
OA	outdoor air
out	to downstream of the system
ref	reference
UVGI	ultra-violet germicidal irradiation
V	ventilation

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