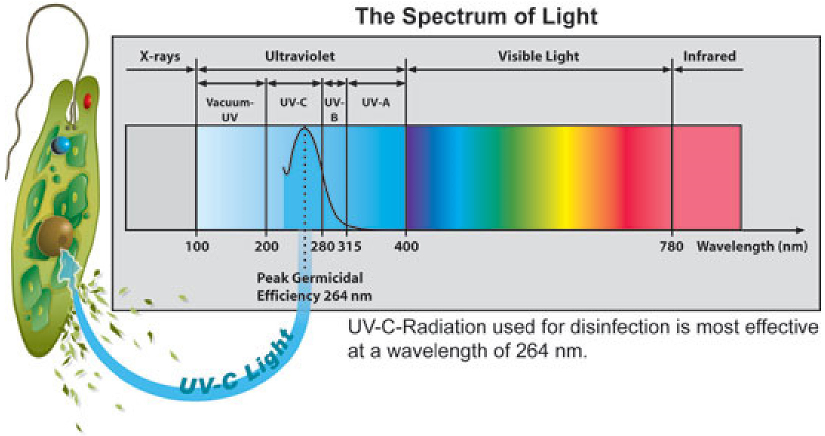
Fundamentals of Ultraviolet Germicidal Irradiation for Air and Surface Disinfection



UV-C-Radiation used for disinfection is most effective at a wavelength of 264 nm.

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Learning Objectives

- Understand dose/response relationships associated with microorganisms exposed to ultraviolet energy.
- Differentiate between the different types of lamps and ballasts commonly used in UVGI systems.
- Recognize the various UVGI technologies used in conjunction with HVAC systems to improve indoor environmental quality and reduce airborne disease transmission.
- Compare the initial capital costs associated with UVGI systems to related energy savings and reductions in HVAC system maintenance costs.
- Understand the maintenance requirements and health and safety considerations associated with UVGI systems.

Outline

- UVGI History
- UVGI Fundamentals
- UVGI Equipment
- Applications and System Design Principles
- Economics of UVGI Applied to HVAC Systems
- Photodegradation of Materials
- UVGI System Maintenance
- UV Health and Safety Considerations
- UVGI Case Study Analysis
- Summary

UVGI History

- Scientific Origins and Applications

Milestones in UVGI History

- 1672 – Separation of light into constituent colors using prisms (Newton)
- 1814 – Spectral bands of sunlight mapped (Fraunhofer)
- 1835 – Mercury vapor arc lamp (Wheatstone)
- 1877 – Germicidal effect of sunlight reported (Downes & Blunt)
- 1889 – Erythemal effects of UV demonstrated (Widmark)
- ***1892 – Germicidal effect of UV on Bacillus anthracis demonstrated (Widmark)***
- 1900 – Use of UV to treat skin disease described (Finsen)
- 1906 – First use of UV to disinfect drinking water
- ***1909 – First UV water treatment plant, Marseille, France***
- 1927 – Bactericidal action of UV quantified (Bedford and Gates)
- 1928 – Viricidal action of UV quantified (Rivers and Gates)
- 1929 – Fungicidal action of UV quantified (Fulton and Coblentz)

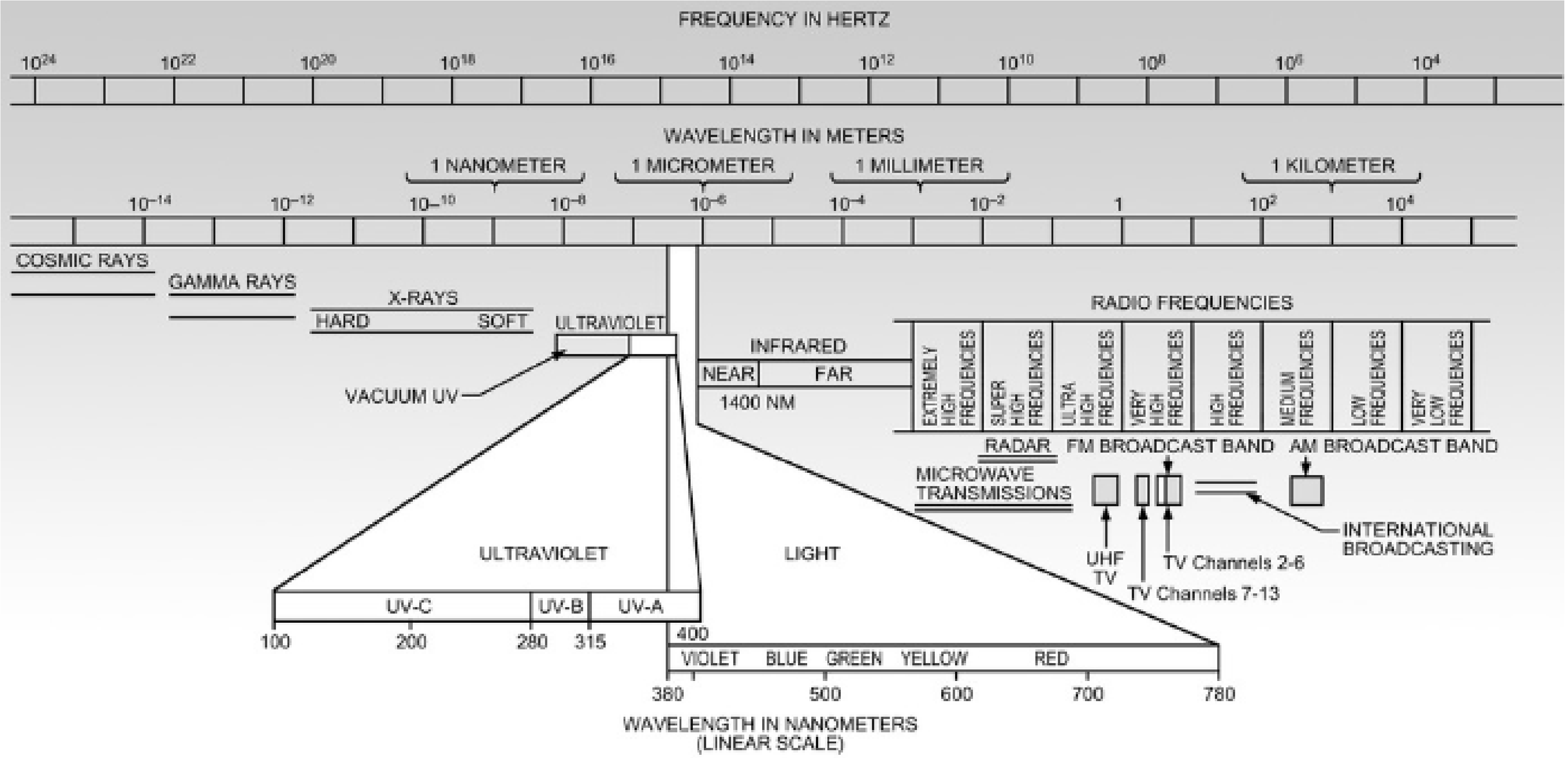
Milestones in UVGI History *(cont.)*

- 1936 – Overhead systems applied in hospitals (Wells and Wells, Hart)
- *1937 – Upper air systems applied in schools (Wells)*
- 1938 – First fluorescent gas discharge UV lamp
- *1940 – Application to HVAC systems (Rentschler and Nagy)*
- 1942 – First sizing guidelines (Luckiesh and Holladay)
- 1950 – First catalog sizing methods (Buttolph and Haynes)
- 1957 – Effectiveness of UV for TB control shown (Riley)
- 1974 – First microbial growth control systems (Grun and Pitz)
- *1999 – WHO recommends UV for TB control*
- *2003 – CDC sanctions use of UV for TB control*
- *2003 – FEMA sanctions UVGI as biodefense option*
- *2005 – ASHRAE Task Group 2.UVAS (later TC 2.9) Ultraviolet Air and Surface Treatment formed*
- *2009 – ASHRAE Position Document on Airborne Infectious Diseases identifies UVGI one of three demonstrated technologies for reducing infection risk*

UVGI Fundamentals

- UV Spectrum
- Microbial Dose Response
- Microbial Susceptibility

UV Spectrum



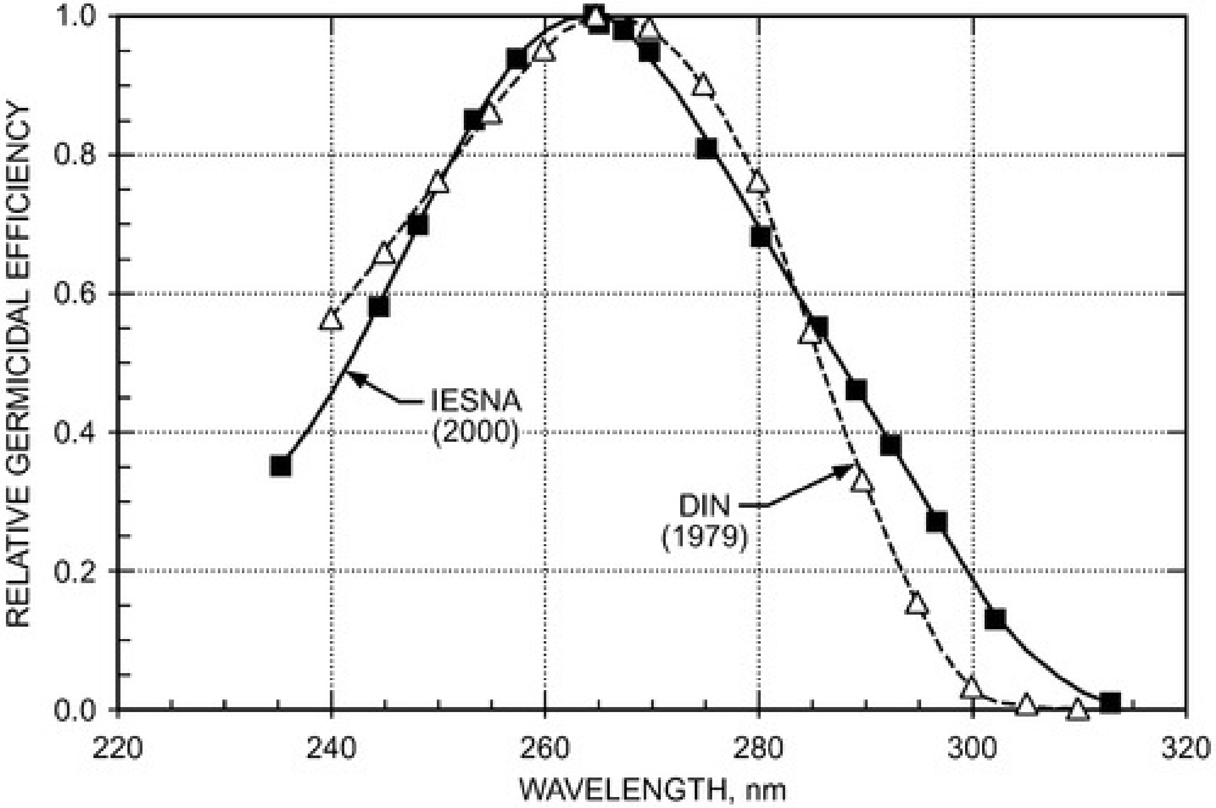
2019 *ASHRAE Handbook—HVAC Applications*, Ch. 62, Fig. 2

Germicidal Action of UVC

- UVC damages DNA/RNA of microorganisms (virus, bacteria, fungi)
- Exponential relation to *dose*, i.e., product of UV strength and duration of exposure
- Microorganisms *inactivated*, i.e., rendered unable to replicate

Germicidal Action Spectrum

Mainly UVC, some UVB effect, max ~265 nm UVC



2019 *ASHRAE Handbook—HVAC Applications*, Ch. 62, Fig. 3

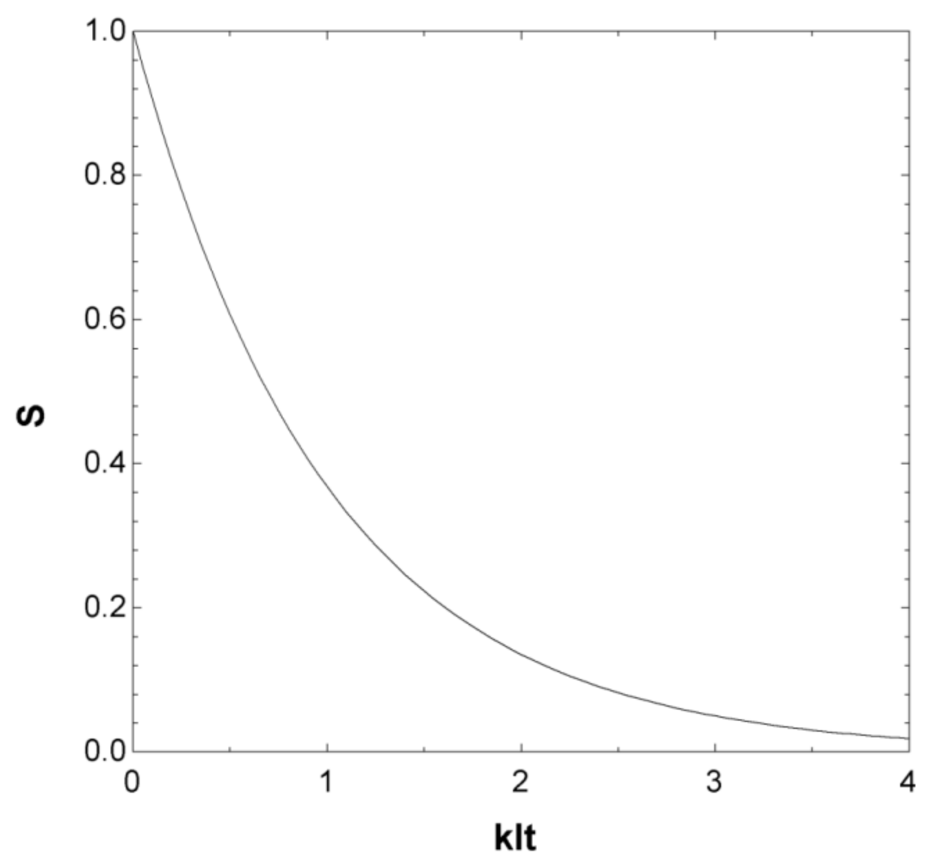
Microbial Dose Response to UVGI

- To a first approximation:

$$S = \exp\left(-kIt\right)$$
$$= \exp\left(-kD\right)$$

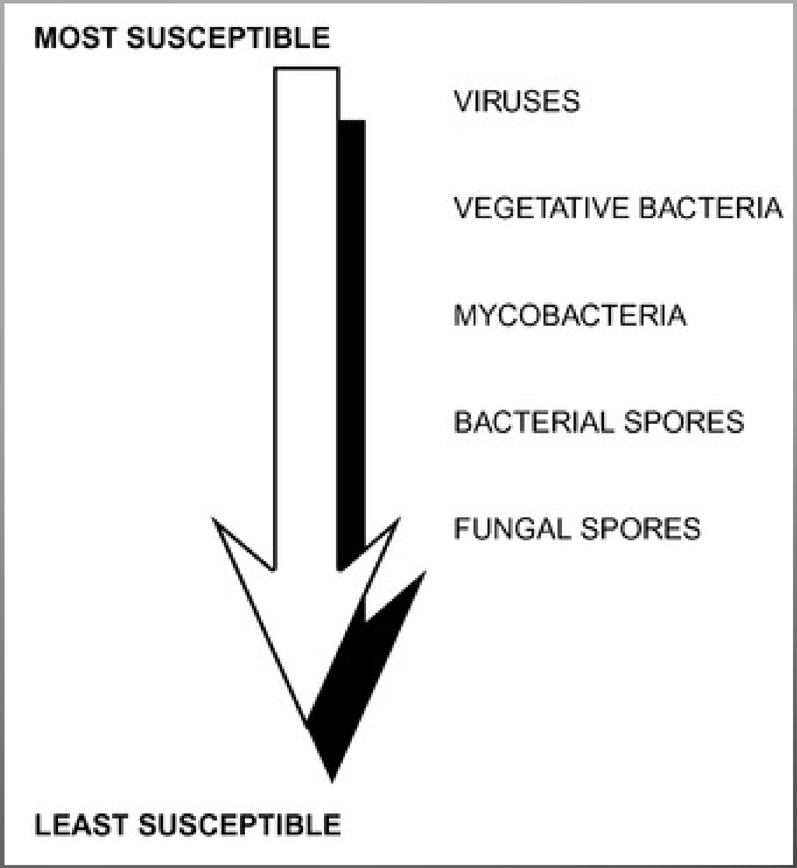
  - S = surviving fraction of initial population
  - k = deactivation rate constant ($\mathrm{cm^2/\mu W\text{-}s}$)
  - I = UV fluence ($\mu\mathrm{W/cm^2}$)
  - t = duration of exposure (s)
  - $It = D$ = “dose” ($\mu\mathrm{J/cm^2}$)

- Chick-Watson model



Microbial Response to UVGI – *k*

- *k* varies by orders of magnitude
- Smaller *k* → more resistant
- Consistent *k* measurement is difficult

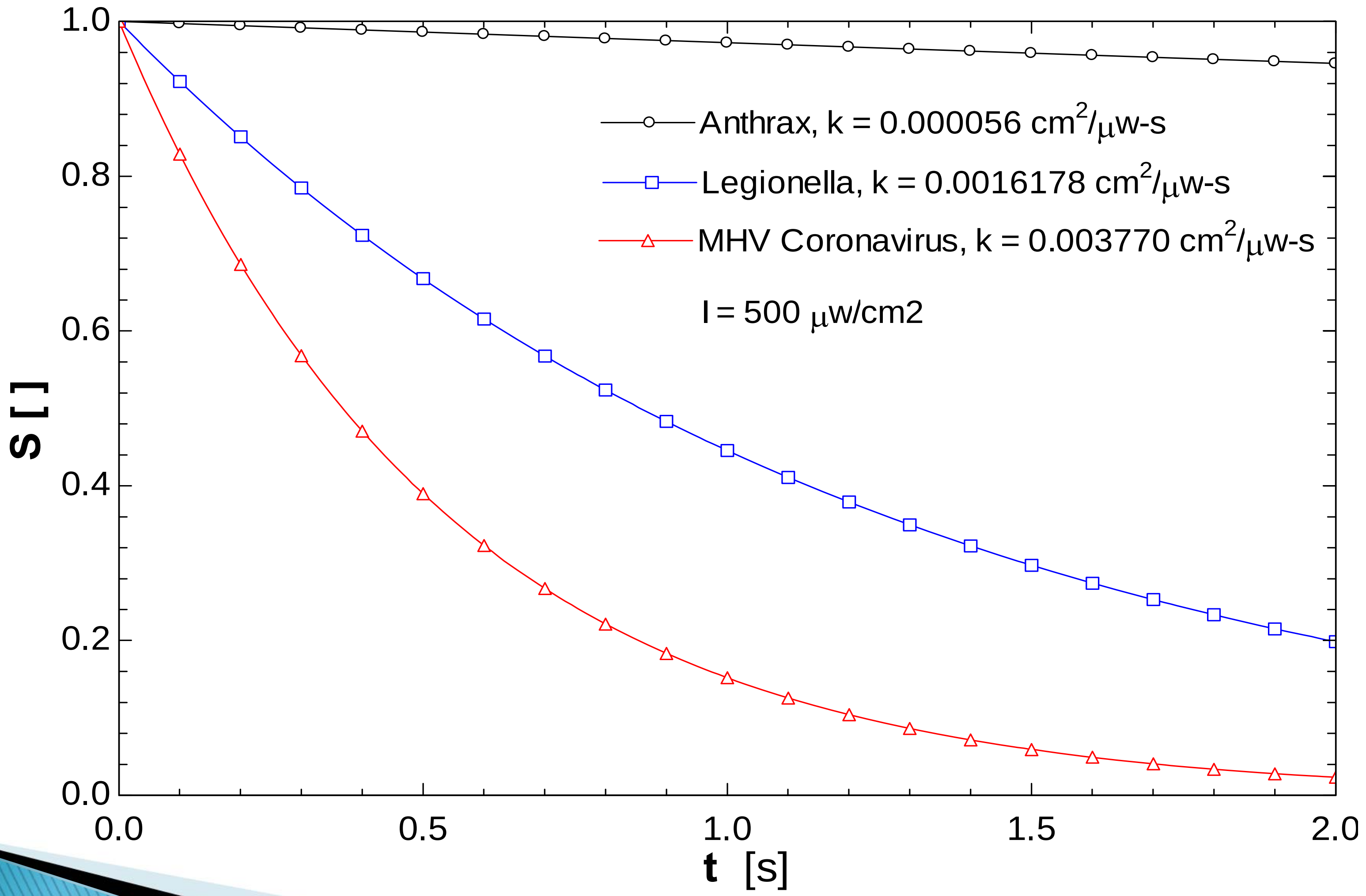


Representative Values ($cm^2/\mu W\text{-}s$)

- *Bacillus anthracis* (bacterial spore)
  - Water: 0.000056
  - Surface: 0.0002702
- *Legionella pneumophila* (vegetative bacteria)
  - Water: 0.0016178
  - Surface: 0.0044613
- *Mycobacterium tuberculosis* (vegetative bacteria)
  - Water: 0.0004773
  - Surface: 0.002132
- Influenza A: 0.0010103 (RNA virus, water)
- MHV Coronavirus: 0.003770 (RNA virus, air @ 50% RH)

Source: Kowalski, Wladyslaw. 2009. *Ultraviolet Germicidal Irradiation Handbook.* Berlin: Springer-Verlag Berlin Heidelberg.

Effect of *k* on Survival



Two-Stage Inactivation

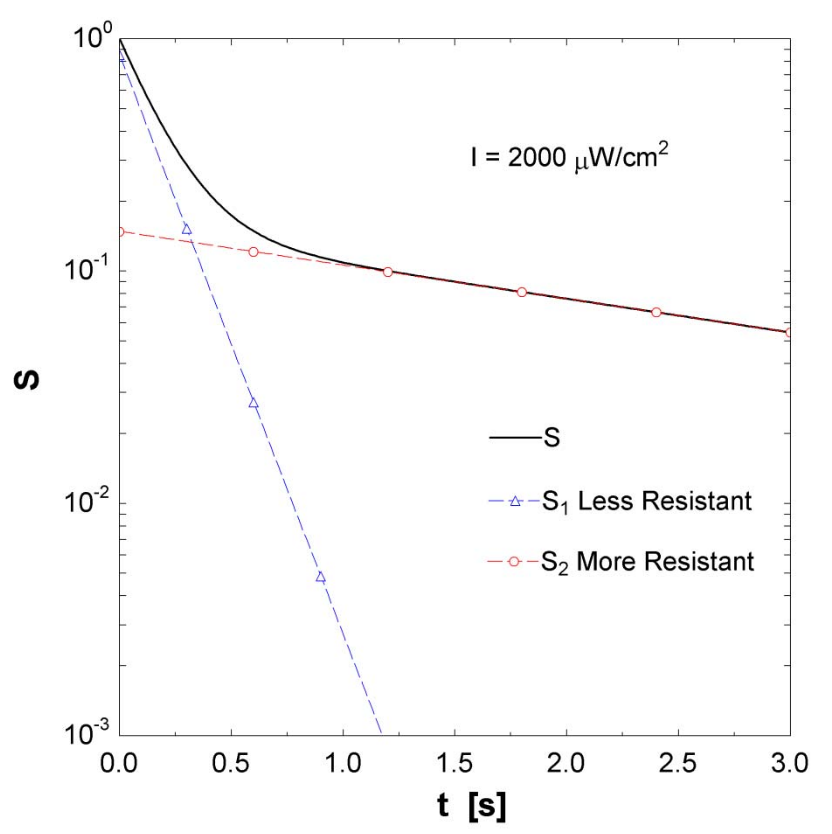
- Behaves *as if* population has a more resistant fraction (*f*) and a less resistant one (1–*f*)

$$S = (1 - f)e^{-k_1 It} + fe^{-k_2 It}$$

- Resistant fraction typically <10%, frequently <<10%

Two-Stage Inactivation Example

- *Streptococcus pyogenes*
- Two-stage
  - $k_1 = 0.00287 \text{cm}^2/\mu\text{W-s}$
    $k_2 = 0.0001670 \text{ cm}^2/\mu\text{W-s}$
    $f = 0.1484$
- $I = 2000\ \mu\text{W/cm}^2$

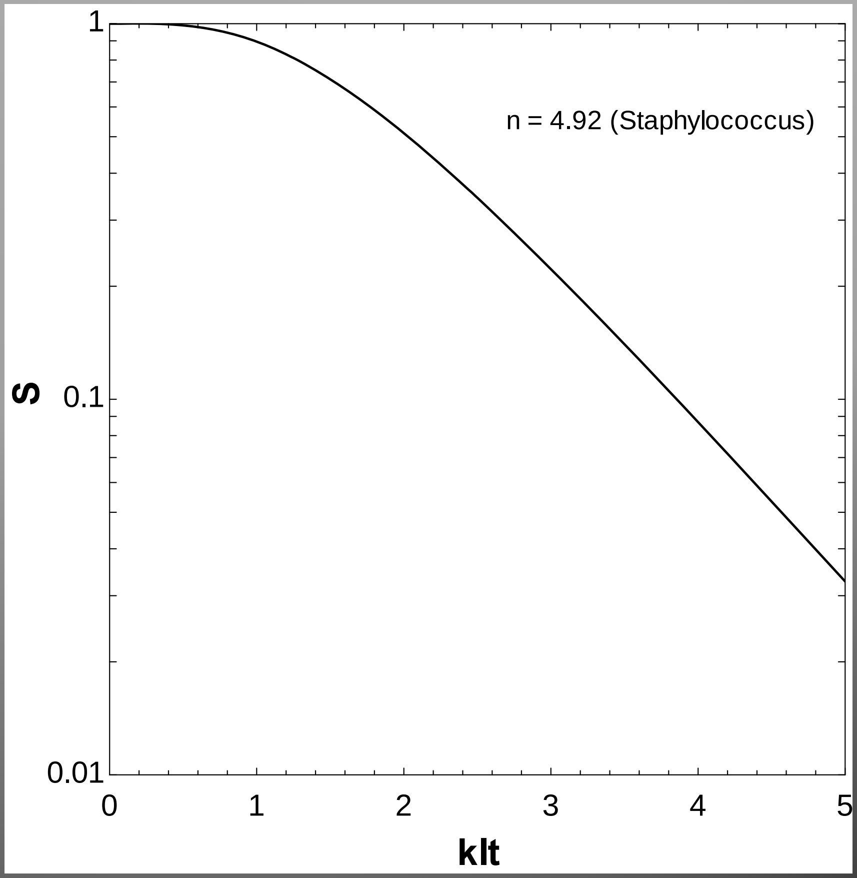


Shoulder Effect

- Slow initial response
- “Multi-hit model”

$$S = 1 - \left(1 - e^{-kIt}\right)^{n}$$

  - n = multi-target exponent



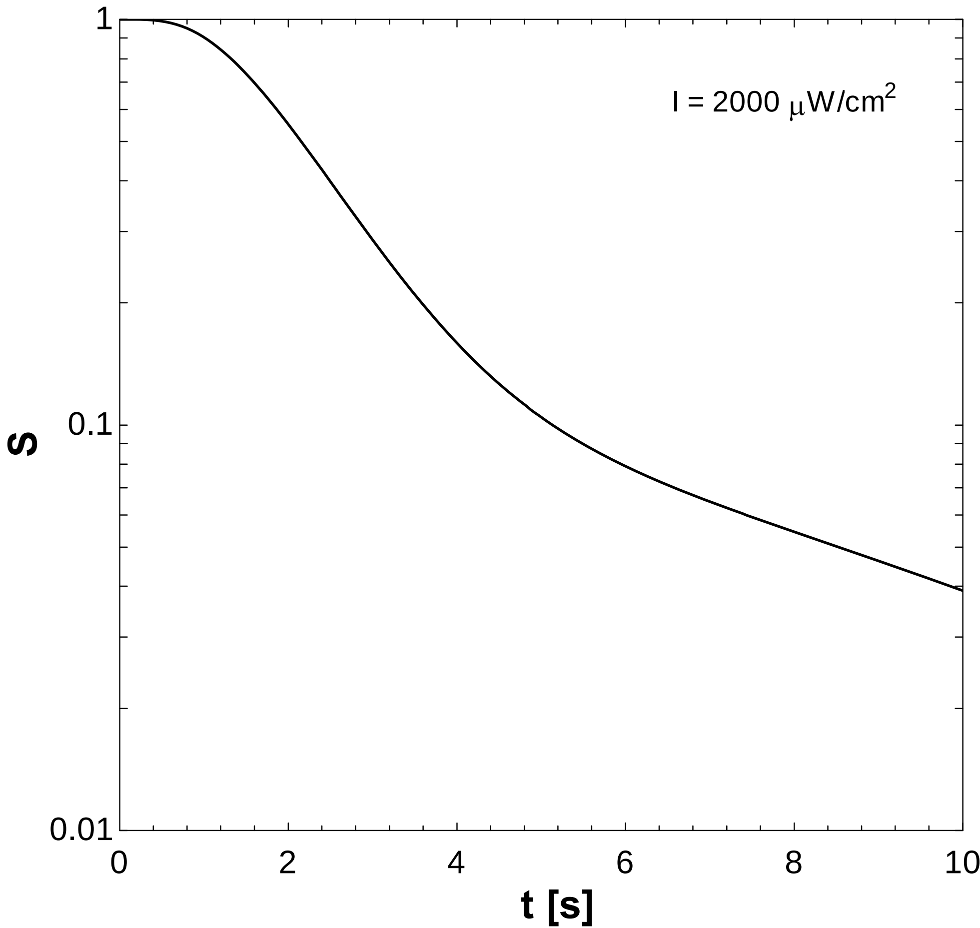
Shoulder + Two-Stage Response

- Can generalize multi-hit model

$$S=(1-f)\left[1-\left(1-e^{-k_1 I t}\right)^{n_1}\right]+f\left[1-\left(1-e^{-k_2 I t}\right)^{n_2}\right]$$

Shoulder + Two-Stage Example

- *Staphylococcus aureus*
  - $k_1 = 0.000500$ cm²/μW-s
  - $k_2 = 0.000108$ cm²/μW-s
    $n_1 = n_2 = 4.9$
  - $f = 0.0860$
- $I = 2000$ μW/cm²



Complicating Factors

- Conditions under which *k* is determined are important, not always documented or controlled
  - Medium of test—water, surface, air
  - Humidity (but not temperature within normal limits)
  - Viability of test samples
  - Handling of test samples
- Photoreactivation—repair of damaged DNA/RNA due to exposure to sunlight

Photoreactivation

- Photoreactivation may partially reverse UV effects
- Knudson (1986) shows effect of light on survival of irradiated anthrax

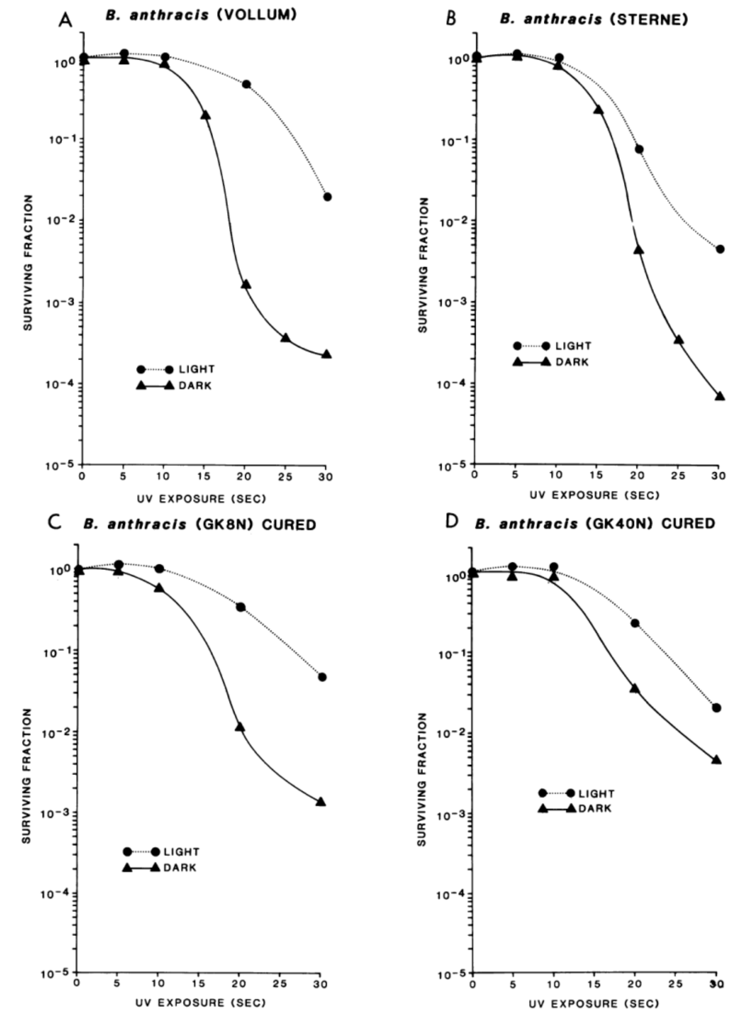


FIG. 4. UV inactivation and photoreactivation of four strains of *B. anthracis*. Survival with photoreactivation light (●) and in the dark (▲) as a function of UV dose.

Appl. Environ. Microbiol. (1986) 52(3): 444-449

Humidity

- Some data suggest impact of humidity on *k*
- More pronounced for bacteria than viruses
- Evidence not definitive for fungi

Viruses

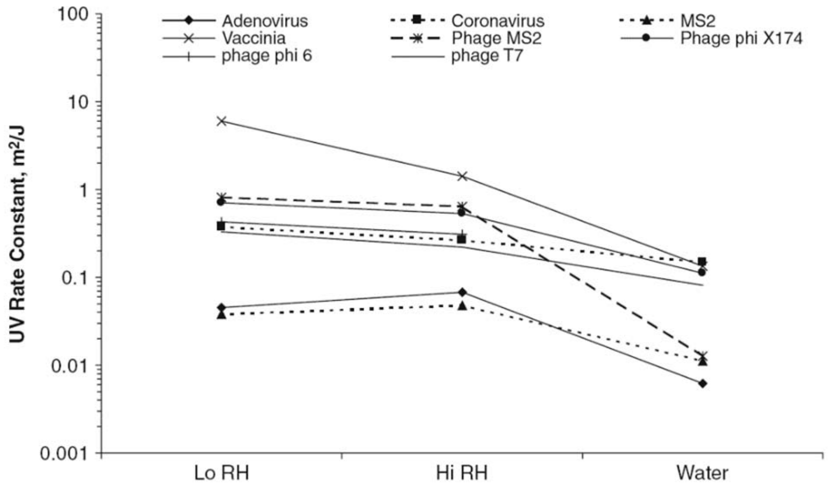


Fig. 3.5 Variation of UV rate constant for viruses in Low to High RH, and compared to Water as an endpoint. Based on data from Table 3.2

Bacteria

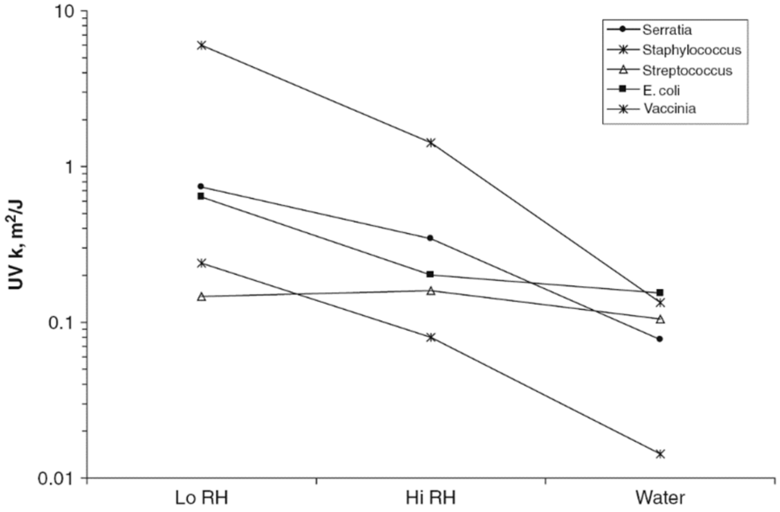


Fig. 3.7 Plot of bacteria UV rate constant variation between low and high RH, and in water as an endpoint. Based on data from Table 3.3

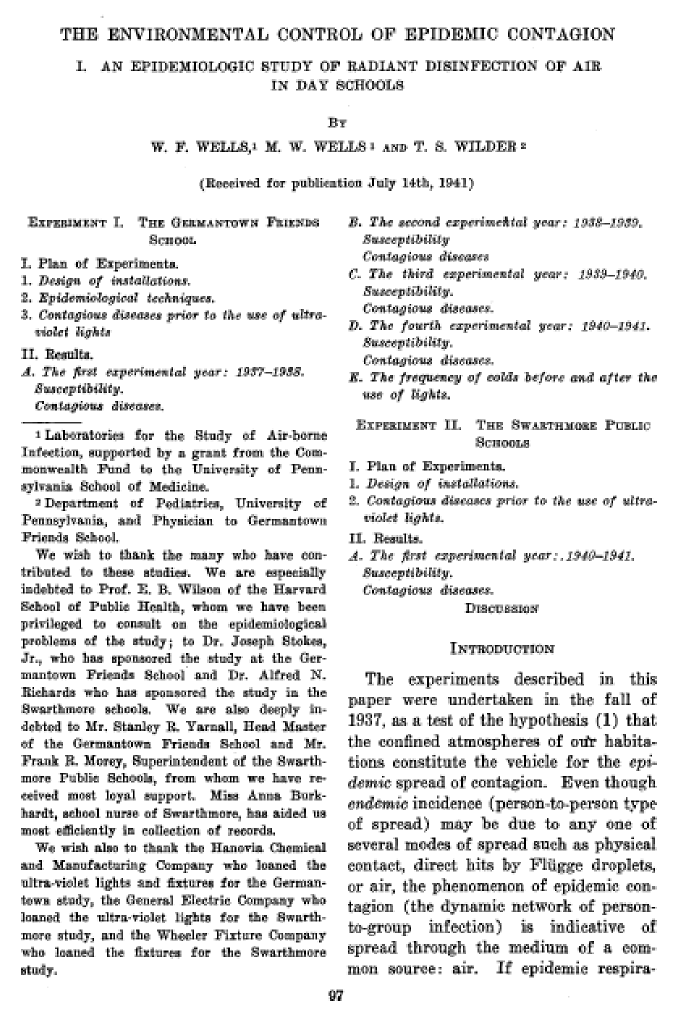
Source: Kowalski, Wladyslaw. 2009. *Ultraviolet Germicidal Irradiation Handbook.* Berlin: Springer-Verlag Berlin Heidelberg.

Documentation of UVGI Effectiveness

- Over 100 years of science evidence and applications to disinfection of water, air, and surfaces
- Multiple scientific studies indicating positive impacts on health outcomes:
  - Control of epidemic disease
  - Reduction of sick building syndrome symptoms
  - Reduction in asthma attacks in children
- Recent studies show effectiveness of cooling coil maintenance

Wells, Wells, and Wilder (1942)
American Journal of Hygiene

- Four years of testing in schools in Philadelphia, PA area
- Upper-room UVGI installed in classrooms
- Tracked infections of susceptible students
- Significantly lower rates of infection of susceptibles in irradiated classrooms



THE ENVIRONMENTAL CONTROL OF EPIDEMIC CONTAGION

I. AN EPIDEMIOLOGIC STUDY OF RADIANT DISINFECTION OF AIR IN DAY SCHOOLS

By

W. F. WELLS,[1] M. W. WELLS[1] AND T. S. WILDER[2]

(Received for publication July 14th, 1941)

EXPERIMENT I. THE GERMANTOWN FRIENDS SCHOOL

I. Plan of Experiments.
1. *Design of installations.*
2. *Epidemiological techniques.*
3. *Contagious diseases prior to the use of ultra-violet lights*

II. Results.
A. The first experimental year: 1937–1938.
  Susceptibility.
  Contagious diseases.
B. The second experimehtal year: 1938–1939.
  Susceptibility
  Contagious diseases
C. The third experimental year: 1939–1940.
  Susceptibility.
  Contagious diseases.
D. The fourth experimental year: 1940–1941.
  Susceptibility.
  Contagious diseases.
E. The frequency of colds before and after the use of lights.

EXPERIMENT II. THE SWARTHMORE PUBLIC SCHOOLS

I. Plan of Experiments.
1. *Design of installations.*
2. *Contagious diseases prior to the use of ultra-violet lights.*

II. Results.
A. The first experimental year: 1940–1941.
  Susceptibility.
  Contagious diseases.

DISCUSSION

INTRODUCTION

The experiments described in this paper were undertaken in the fall of 1937, as a test of the hypothesis (1) that the confined atmospheres of our habitations constitute the vehicle for the *epidemic* spread of contagion. Even though *endemic* incidence (person-to-person type of spread) may be due to any one of several modes of spread such as physical contact, direct hits by Flügge droplets, or air, the phenomenon of epidemic contagion (the dynamic network of person-to-group infection) is indicative of spread through the medium of a common source: air. If epidemic respira-

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[1] Laboratories for the Study of Air-borne Infection, supported by a grant from the Commonwealth Fund to the University of Pennsylvania School of Medicine.

[2] Department of Pediatrics, University of Pennsylvania, and Physician to Germantown Friends School.

We wish to thank the many who have contributed to these studies. We are especially indebted to Prof. E. B. Wilson of the Harvard School of Public Health, whom we have been privileged to consult on the epidemiological problems of the study; to Dr. Joseph Stokes, Jr., who has sponsored the study at the Germantown Friends School and Dr. Alfred N. Richards who has sponsored the study in the Swarthmore schools. We are also deeply indebted to Mr. Stanley R. Yarnall, Head Master of the Germantown Friends School and Mr. Frank R. Morey, Superintendent of the Swarthmore Public Schools, from whom we have received most loyal support. Miss Anna Burkhardt, school nurse of Swarthmore, has aided us most efficiently in collection of records.

We wish also to thank the Hanovia Chemical and Manufacturing Company who loaned the ultra-violet lights and fixtures for the Germantown study, the General Electric Company who loaned the ultra-violet lights for the Swarthmore study, and the Wheeler Fixture Company who loaned the fixtures for the Swarthmore study.

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Wells, Wells, and Wilder (1942)
American Journal of Hygiene

FIGURE 1. Classroom, Germantown Friends School, central radiant sources.

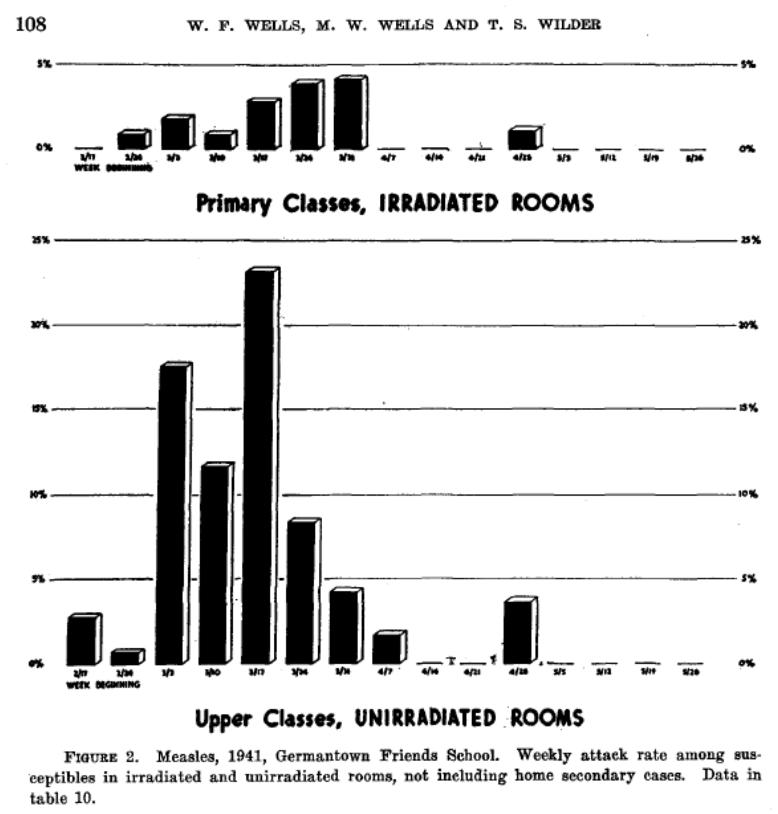

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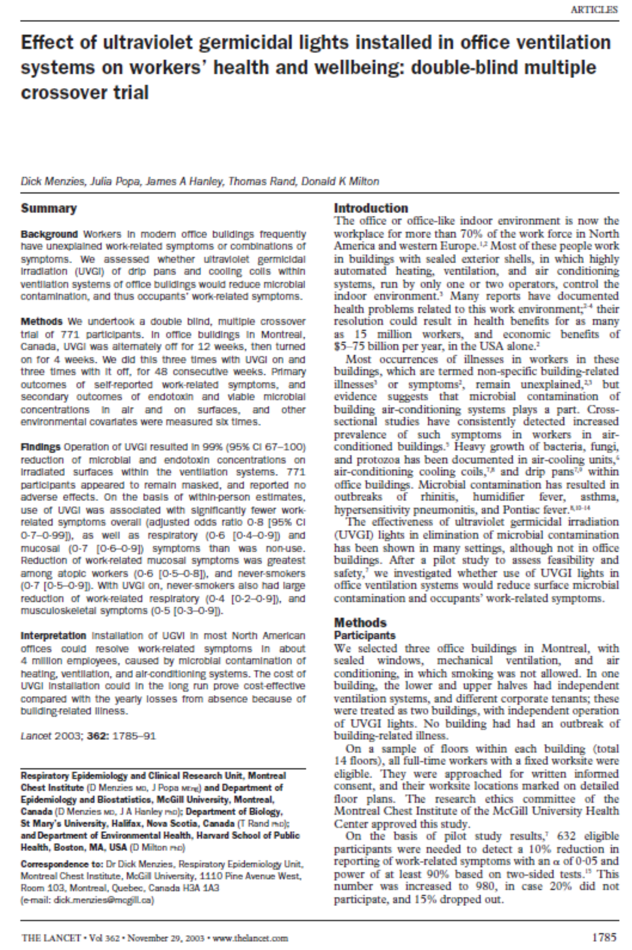
FIGURE 2. Measles, 1941, Germantown Friends School. Weekly attack rate among susceptibles in irradiated and unirradiated rooms, not including home secondary cases. Data in table 10.

Menzies, *et al.* (2003) *Lancet*

- UVGI in AHUs on 12 weeks, off 4 for total of 48 weeks
- 771 subjects
- Self-reported symptoms
- Microbial and endotoxin measurements



Effect of ultraviolet germicidal lights installed in office ventilation systems on workers' health and wellbeing: double-blind multiple crossover trial

Dick Menzies, Julia Popa, James A Hanley, Thomas Rand, Donald K Milton

Summary

Background Workers in modern office buildings frequently have unexplained work-related symptoms or combinations of symptoms. We assessed whether ultraviolet germicidal irradiation (UVGI) of drip pans and cooling coils within ventilation systems of office buildings would reduce microbial contamination, and thus occupants' work-related symptoms.

Methods We undertook a double blind, multiple crossover trial of 771 participants. In office buildings in Montreal, Canada, UVGI was alternately off for 12 weeks, then turned on for 4 weeks. We did this three times with UVGI on and three times with it off, for 48 consecutive weeks. Primary outcomes of self-reported work-related symptoms, and secondary outcomes of endotoxin and viable microbial concentrations in air and on surfaces, and other environmental covariates were measured six times.

Findings Operation of UVGI resulted in 99% (95% CI 67–100) reduction of microbial and endotoxin concentrations on irradiated surfaces within the ventilation systems. 771 participants appeared to remain masked, and reported no adverse effects. On the basis of within-person estimates, use of UVGI was associated with significantly fewer work-related symptoms overall (adjusted odds ratio 0·8 [95% CI 0·7–0·99]), as well as respiratory (0·6 [0·4–0·9]) and mucosal (0·7 [0·6–0·9]) symptoms than was non-use. Reduction of work-related mucosal symptoms was greatest among atopic workers (0·6 [0·5–0·8]), and never-smokers (0·7 [0·5–0·9]). With UVGI on, never-smokers also had large reduction of work-related respiratory (0·4 [0·2–0·9]), and musculoskeletal symptoms (0·5 [0·3–0·9]).

Interpretation Installation of UGVI in most North American offices could resolve work-related symptoms in about 4 million employees, caused by microbial contamination of heating, ventilation, and air-conditioning systems. The cost of UVGI installation could in the long run prove cost-effective compared with the yearly losses from absence because of building-related illness.

Lancet 2003; **362:** 1785–91

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Introduction

The office or office-like indoor environment is now the workplace for more than 70% of the work force in North America and western Europe.[1,2] Most of these people work in buildings with sealed exterior shells, in which highly automated heating, ventilation, and air conditioning systems, run by only one or two operators, control the indoor environment.[3] Many reports have documented health problems related to this work environment;[2–4] their resolution could result in health benefits for as many as 15 million workers, and economic benefits of $5–75 billion per year, in the USA alone.[2]

Most occurrences of illnesses in workers in these buildings, which are termed non-specific building-related illnesses[3] or symptoms[2], remain unexplained,[2,3] but evidence suggests that microbial contamination of building air-conditioning systems plays a part. Cross-sectional studies have consistently detected increased prevalence of such symptoms in workers in air-conditioned buildings.[5] Heavy growth of bacteria, fungi, and protozoa has been documented in air-cooling units,[6] air-conditioning cooling coils,[7,8] and drip pans[7,9] within office buildings. Microbial contamination has resulted in outbreaks of rhinitis, humidifier fever, asthma, hypersensitivity pneumonitis, and Pontiac fever.[8,10–14]

The effectiveness of ultraviolet germicidal irradiation (UVGI) lights in elimination of microbial contamination has been shown in many settings, although not in office buildings. After a pilot study to assess feasibility and safety,[7] we investigated whether use of UVGI lights in office ventilation systems would reduce surface microbial contamination and occupants' work-related symptoms.

Methods

Participants

We selected three office buildings in Montreal, with sealed windows, mechanical ventilation, and air conditioning, in which smoking was not allowed. In one building, the lower and upper halves had independent ventilation systems, and different corporate tenants; these were treated as two buildings, with independent operation of UVGI lights. No building had had an outbreak of building-related illness.

On a sample of floors within each building (total 14 floors), all full-time workers with a fixed worksite were eligible. They were approached for written informed consent, and their worksite locations marked on detailed floor plans. The research ethics committee of the Montreal Chest Institute of the McGill University Health Center approved this study.

On the basis of pilot study results,[7] 632 eligible participants were needed to detect a 10% reduction in reporting of work-related symptoms with an α of 0·05 and power of at least 90% based on two-sided tests.[15] This number was increased to 980, in case 20% did not participate, and 15% dropped out.

Menzies, *et al.* (2003) *Lancet*

- Findings
  - 99% reduction of microbial and endotoxin concentrations on irradiated surfaces
  - No adverse effects
  - Statistically significant reduction of symptoms
  - “The cost of UVGI could in the long run prove cost-effective compared with the yearly losses from absence because of building-related illness”

Bernstein, et al. (2006) *Journal of Asthma*

- Double-blind study with central UVGI in homes of 19 mold-sensitized asthmatic children
- Statistically significant improvement in morning and evening peak expiratory air flow rate with UVGI operation

Journal of Asthma, 43:255–262, 2006
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ORIGINAL ARTICLE

Health Effects of Ultraviolet Irradiation in Asthmatic Children's Homes

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Objective. Centrally installed ultraviolet (UV) irradiation units were investigated to determine the potential health benefits in mold-sensitized asthmatic children. *Methods.* Nineteen mold-sensitized asthmatic children 5 to 17 years of age with home central ventilation systems were enrolled in a 28-week double-blinded placebo controlled cross-over trial. Clinical outcome measurements included morning and evening peak expiratory flow rates (PEFR), PEFR variability, change in forced expiratory volume in 1 second (FEV_1), change in total rhinoconjunctivitis and asthma symptom scores, change in rhinoconjunctivitis and asthma quality-of-life scores, and total (rescue and controller) medication use from baseline and between time periods. Environmental outcomes included changes in temperature, relative humidity, dew point, and indoor airborne mold and bacterial counts from baseline and between time periods. Analysis of variance (ANOVA) and regression analysis and t test were used to evaluate relationships between environmental exposure(s) and clinical outcome measurements during each study period. *Results.* Twelve male and seven female children, average age 10.6 years, were enrolled. A statistically significant improvement in PEFR variability in subjects receiving CREON2000 units followed by placebo units was observed ($p < 0.05$) across both treatment periods. Within group analysis during treatment period 1, a statistically significant improvement in reduction of asthma symptom scores, the number of days with asthma symptoms, total asthma medication use, and PEFR variability were observed in subjects receiving CREON2000 units versus placebo units ($p < 0.05$). No significant differences were observed between the CREON 2000 and placebo units for other clinical or environmental outcome measurements. *Conclusions.* Central UV irradiation was effective at reducing airway hyperresponsiveness manifested as PEFR variability and some clinical symptoms. A larger cohort controlled longitudinal study to validate the clinical health effects of UV irradiation as a primary indoor environmental intervention for allergic asthma is necessary to confirm this finding.

Keywords ultraviolet irradiation, CREON2000, asthma, rhinoconjunctivitis, quality of life, mold exposure, bacteria exposure, health effects

INTRODUCTION

The prevalence of asthma and allergies has increased 75% between 1980 and 1994 in the United States with the greatest increase in children (approximately a 160% increase) (1, 2). The rising prevalence of asthma is reflected in increased hospitalization rates and overall health care costs (2). It is widely believed that an important contributing factor to the rising prevalence of asthma is poor indoor air quality.

Indoor environments are sources of many common allergens including dust mites, mold spores, cockroaches, and pets and their by-products, all of which have been linked with adverse health effects. The relationship between allergen exposure, sensitization, and the development of asthma is strengthened by numerous studies that have found that a reduction or elimination of the offending allergen(s) improves clinical outcomes (3, 4).

Studies have demonstrated a relationship between airborne mold spore levels and asthma exacerbations (5–7). This relationship is supported by numerous epidemiologic studies that have identified a significant relationship between home dampness and increased respiratory infections and asthma (8–11). The difficulty in establishing a causal effect between indoor mold exposure and respiratory problems including asthma has been largely due to multiple confounding variables that make it difficult to design clinical trials (8).

Spread of airborne microbial agents has been well documented to be reduced by ultraviolet (UV) irradiation systems installed inside ventilation air duct systems (12–16). Ultraviolet irradiation has proven to be more effective and economically feasible than other approaches in reducing levels of indoor microorganisms. Current commercially available UV air disinfection systems have low energy efficiency and reliability because particles suspended in the air accumulate on the surface of the lamp, which reduces or eliminates their germicidal effectiveness (17–19). The CREON2000 Photonic Air Disinfection system (US patent 5,635,133; European patent 0848617) has been demonstrated to continuously operate efficiently because of a pre-filter system that removes dust from the treated air thereby preventing dust accumulation on the lamps over time (20).

Very few studies have been conducted to determine the health benefits of UV air disinfection systems. Menzies et al. conducted a study to investigate whether UV irradiation of drip pans and cooling coils in ventilation systems of office buildings was effective at reducing microbial contamination, thereby reducing work-related symptoms (21). A double-blind multiple cross-over study was conducted with 771

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Wong, et al. (2016)
American Journal of Infection Control

- Comparison of normal cleaning and UVC room decontamination no HAI pathogens (Wong, et al. 2016)
- Conventional cleaning (peroxide and detergent) or automated UV
- Cleaning – no significant change in number of rooms where contamination was detected
- UV – large reduction in contaminated rooms and in counts

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AJIC American Journal of Infection Control

Major article

Postdischarge decontamination of MRSA, VRE, and *Clostridium difficile* isolation rooms using 2 commercially available automated ultraviolet-C–emitting devices

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Reported Effectiveness – Room Disinfection

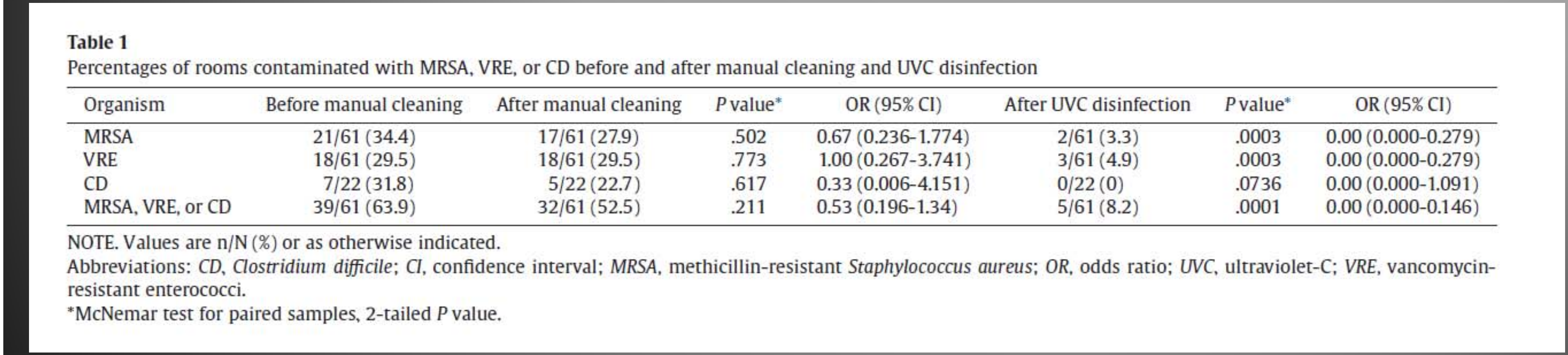


Table 1

Percentages of rooms contaminated with MRSA, VRE, or CD before and after manual cleaning and UVC disinfection

Organism	Before manual cleaning	After manual cleaning	*P* value*	OR (95% CI)	After UVC disinfection	*P* value*	OR (95% CI)
MRSA	21/61 (34.4)	17/61 (27.9)	.502	0.67 (0.236-1.774)	2/61 (3.3)	.0003	0.00 (0.000-0.279)
VRE	18/61 (29.5)	18/61 (29.5)	.773	1.00 (0.267-3.741)	3/61 (4.9)	.0003	0.00 (0.000-0.279)
CD	7/22 (31.8)	5/22 (22.7)	.617	0.33 (0.006-4.151)	0/22 (0)	.0736	0.00 (0.000-1.091)
MRSA, VRE, or CD	39/61 (63.9)	32/61 (52.5)	.211	0.53 (0.196-1.34)	5/61 (8.2)	.0001	0.00 (0.000-0.146)

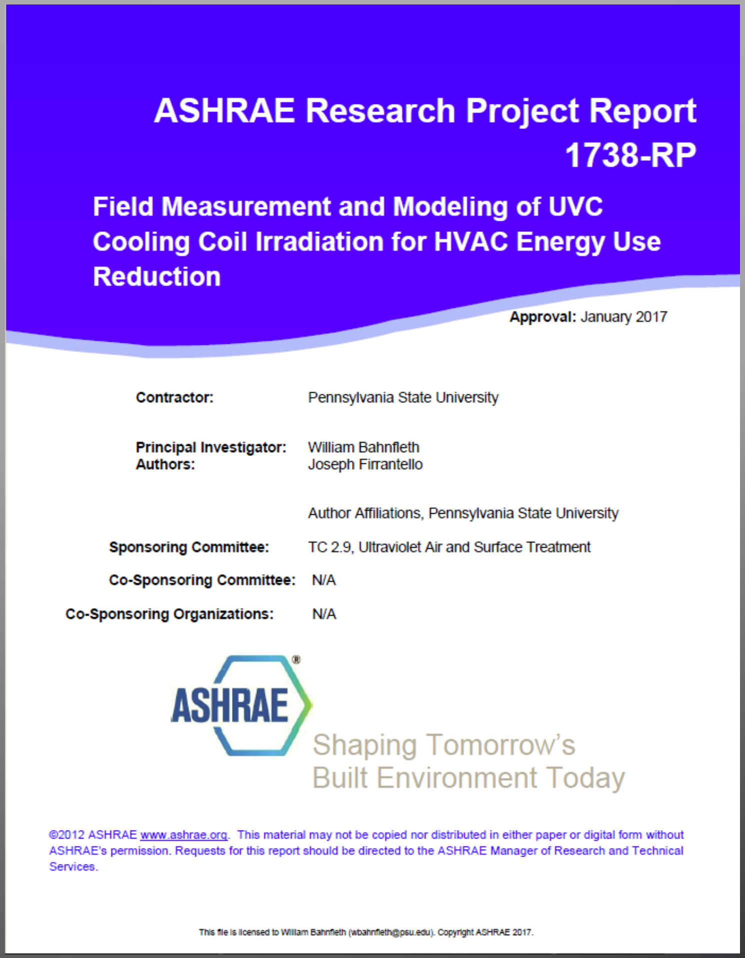
NOTE. Values are n/N (%) or as otherwise indicated.

Abbreviations: *CD*, *Clostridium difficile*; *CI*, confidence interval; *MRSA*, methicillin-resistant *Staphylococcus aureus*; *OR*, odds ratio; *UVC*, ultraviolet-C; *VRE*, vancomycin-resistant enterococci.

*McNemar test for paired samples, 2-tailed *P* value.

Bahnfleth and Firrantello (2017)
ASHRAE 1738-RP

- Field studies of two chilled-water coils before and after coil UVGI
- Energy-use related measurements
- Tampa, Florida science building
  - ~22% reduction in ΔP
  - ~15% increase in overall conductance
  - Results similar to Yi, et al. (2016, 2017) in Singapore laboratory building



ASHRAE Research Project Report
1738-RP

Field Measurement and Modeling of UVC Cooling Coil Irradiation for HVAC Energy Use Reduction

Approval: January 2017

Contractor: Pennsylvania State University

Principal Investigator: William Bahnfleth
Authors: Joseph Firrantello

Author Affiliations, Pennsylvania State University

Sponsoring Committee: TC 2.9, Ultraviolet Air and Surface Treatment

Co-Sponsoring Committee: N/A

Co-Sponsoring Organizations: N/A

ASHRAE

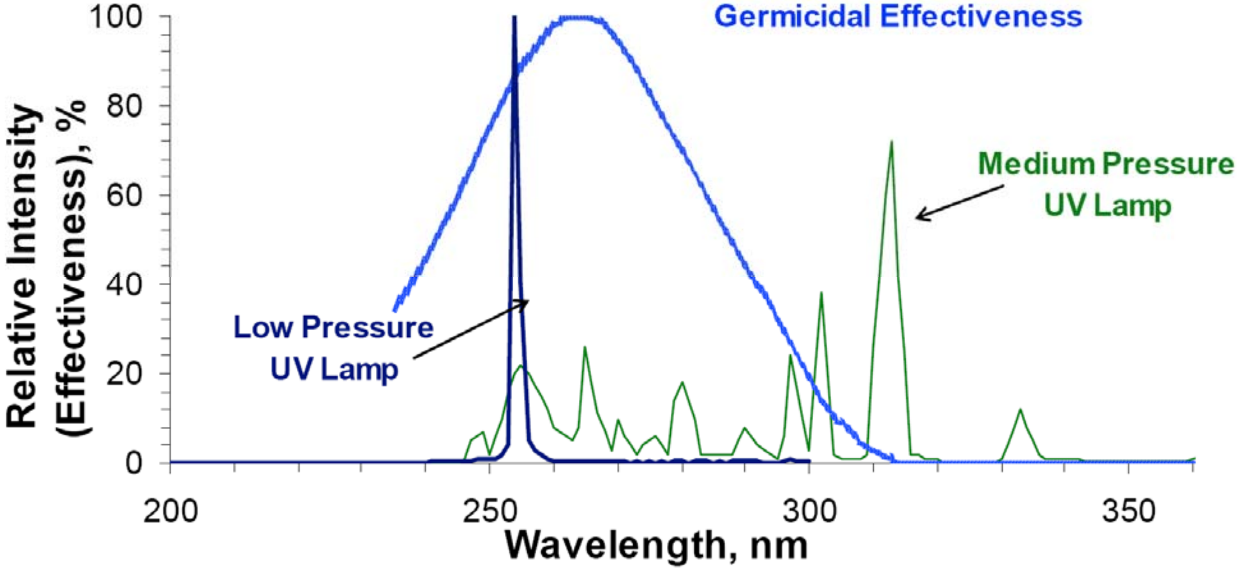
Shaping Tomorrow's
Built Environment Today

UVGI Equipment

- Mercury Vapor Lamps
- Ballasts
- Impact of Ballast Selection
- Operating Characteristics
- Effects of Important Environmental Factors
- Emerging Technologies

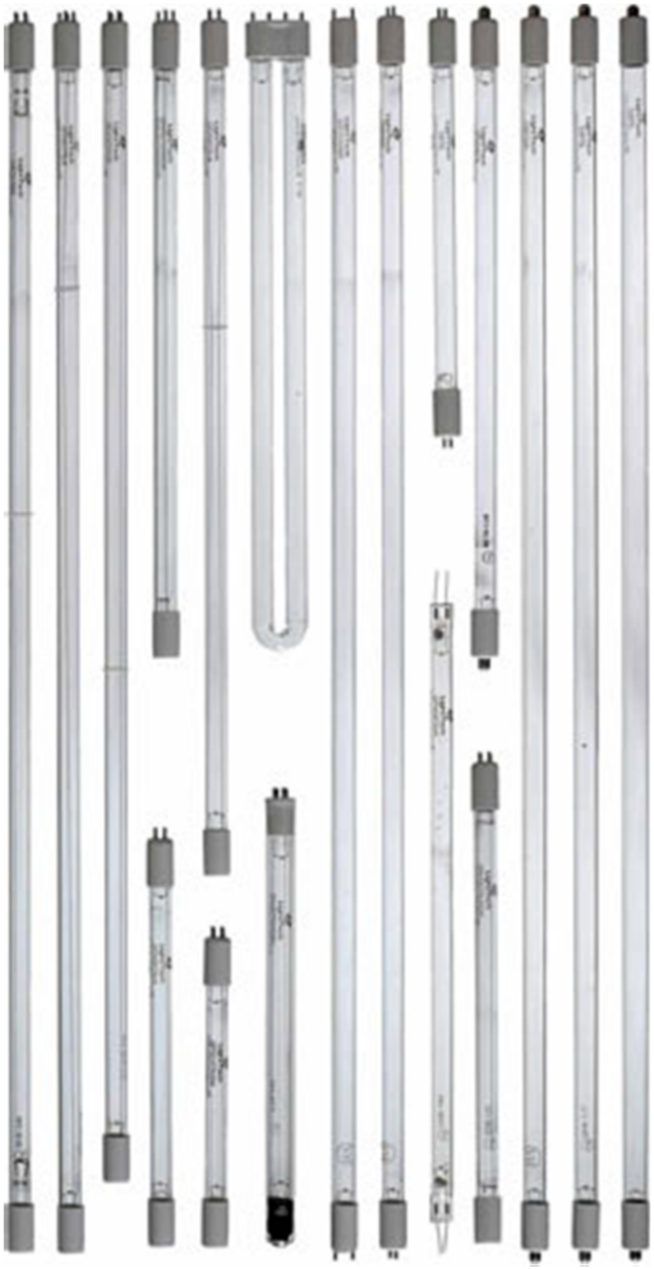
Lamps

- Current generation uses same technology as fluorescent lamps
- Typical lamp
  - Low pressure Hg vapor or amalgam lamp
  - Electric field excites vapor, which emits UVC mainly at 253.7 nm
  - UVC nominally ~20%–30% of input power
  - Quartz or soft glass tube with high UVC transmittance

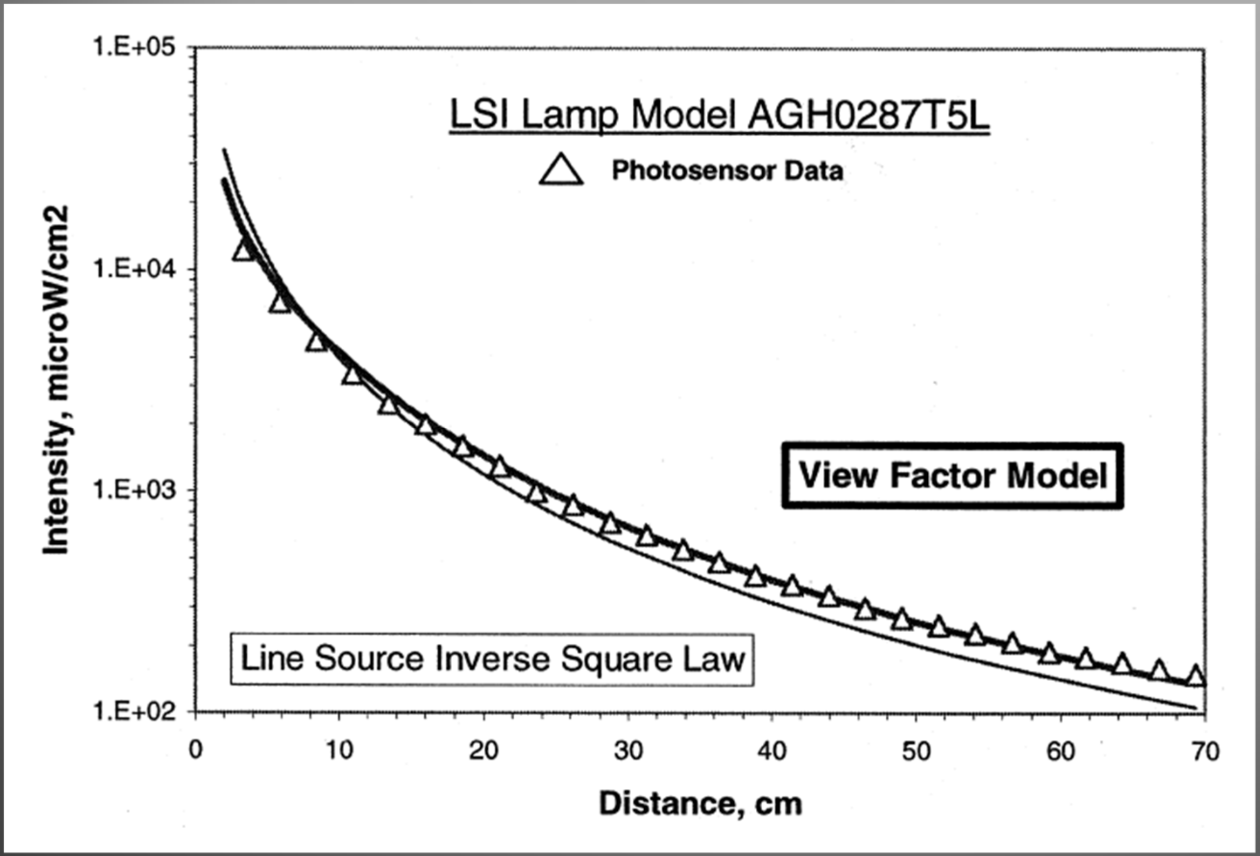


Lamps

- Lamp shapes
  - Single tube
  - Biaxial (twin tube)
  - U-tube



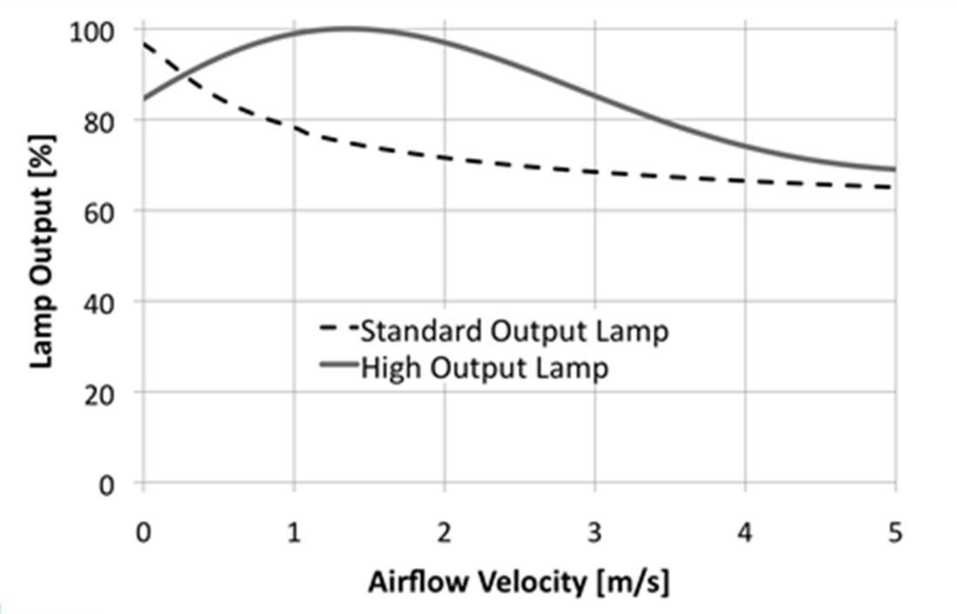
Direct Irradiance vs. Distance – Inverse Square Law



Reflective enclosure greatly improves performance

Lamps

- Output Level
  - Standard output (425 ma)
  - High output (800–1200 ma)
  - *High output lamps may operate at higher temperature than standard output lamps, with benefit for some applications*



Note: 1 m/s ≅ 198 fpm

Lamps

- Cathode types
  - Hot cathode
    - Coated filament, thermionic effect
    - Higher output than cold cathode
    - Starts affect life
  - Cold cathode
    - High-voltage potential ionizes gas in lamp
    - Lower power/output than hot cathode
    - Long life, not affected by starts

Ballasts

- Ballast = power supply
- Provides high starting voltage, then controls to safe operating current
- Ballasts should be matched with lamp per manufacturer’s recommendations

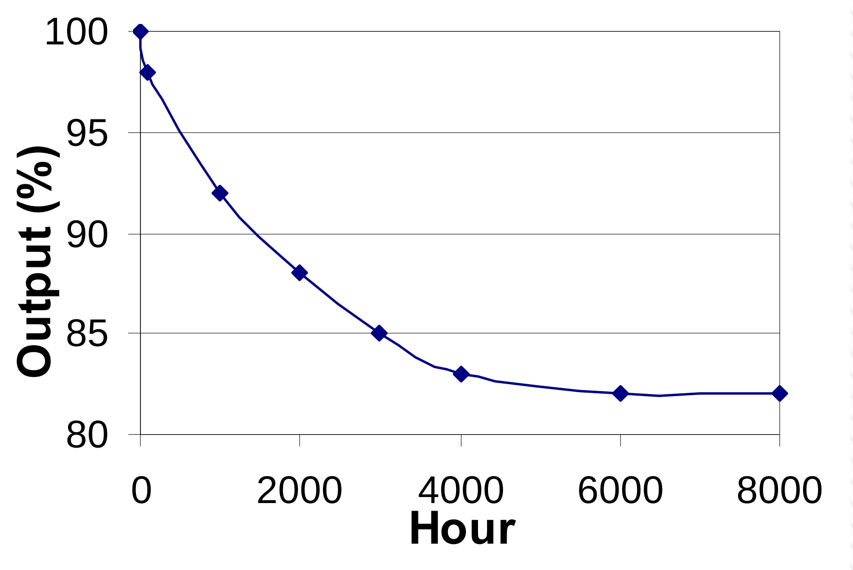
- Starting mode
  - Preheat
  - Rapid start
  - Instant start
- Types
  - Magnetic
  - Electronic
- Dimming ballasts are available but not in common use

Impact of Ballast Selection on Lamp Performance

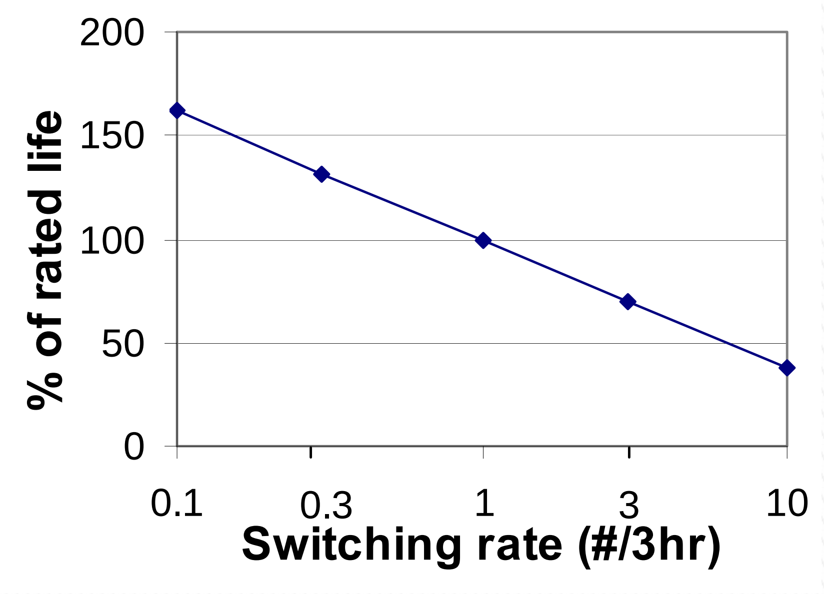
- Ballast selection affects lamp…
  - Output
  - Life
    - Hot cathode ~5000 – 10,000 h (affected by cycling)
    - Cold cathode ~20,000 h
  - Efficiency (e.g., high frequency electronic vs. electromagnetic)
- Ballast may also create audible noise (electromagnetic), EMI/RFI (electronic), and affect power quality

Lamp Depreciation and Life

Depreciation minimally ~15% but may be up to 50%
Typical life ~8000 h for hot cathode, but affected by application



Depreciation

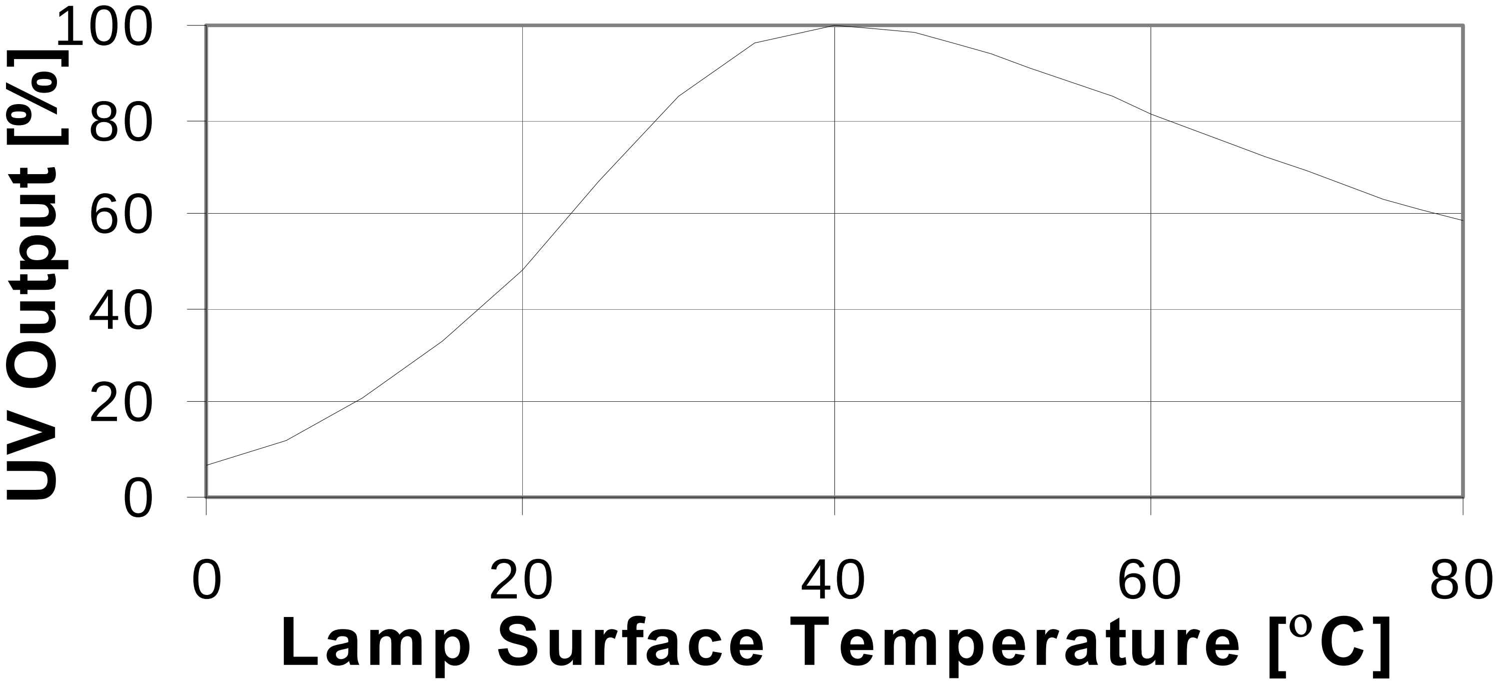


Hot Cathode Life

Wind Chill

- Lamp output depends on vapor pressure inside lamp
- Vapor pressure controlled by the coldest temperature on the lamp tube—“cold spot temperature”
- Cold spot temperature depends on:
  - Lamp shape
  - Lamp orientation
  - Air velocity and temperature
  - Power input to lamp
- Standard rating conditions—room temperature, still air—often do not represent application conditions
- Sleeved lamps reduce wind chill but at significant cost

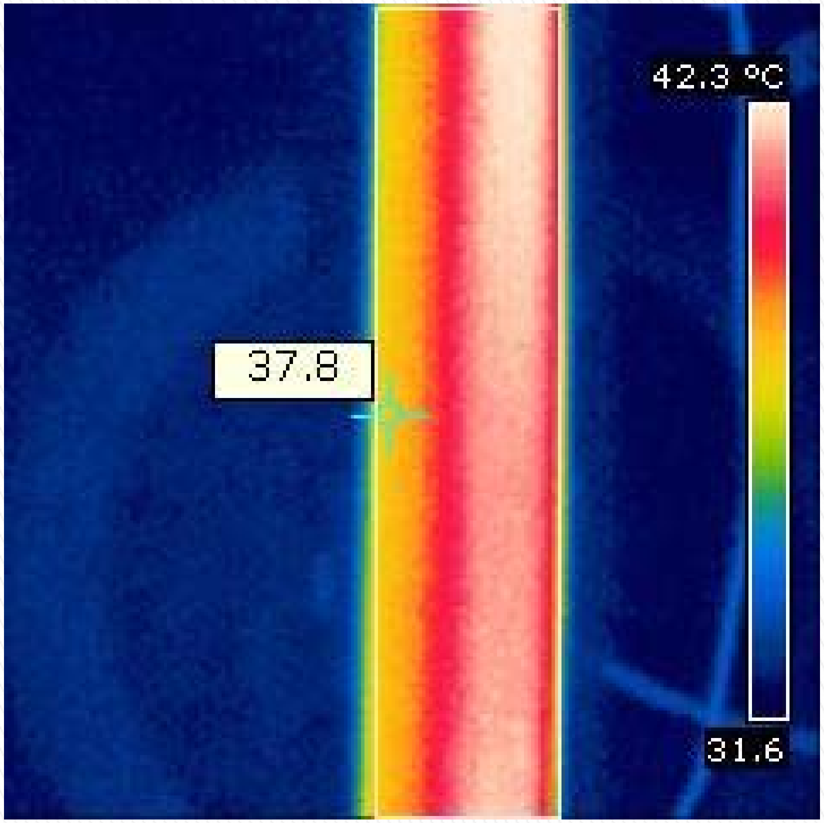
Typical Wind Chill Curve



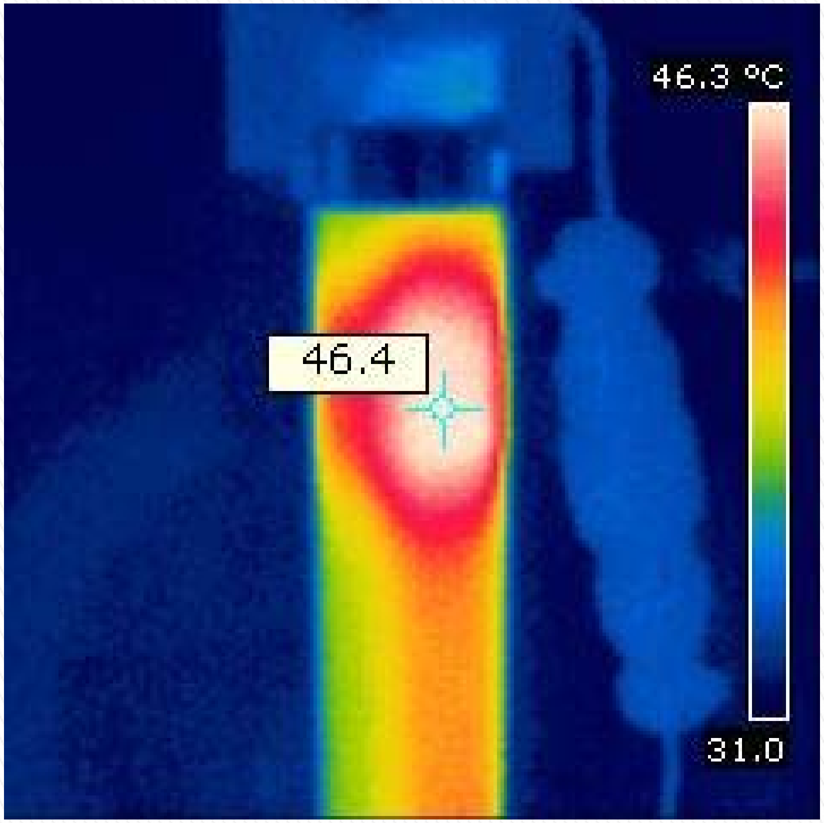
Maximum output when cold spot T = 40°C (109°F)
[Note - 0°C = 32°F, 80°C = 176°F]

Temperature of Lamp in Cross Flow

Conditions: 32.2°C (90.0°F), 1.78 m/s (350 ft/min)



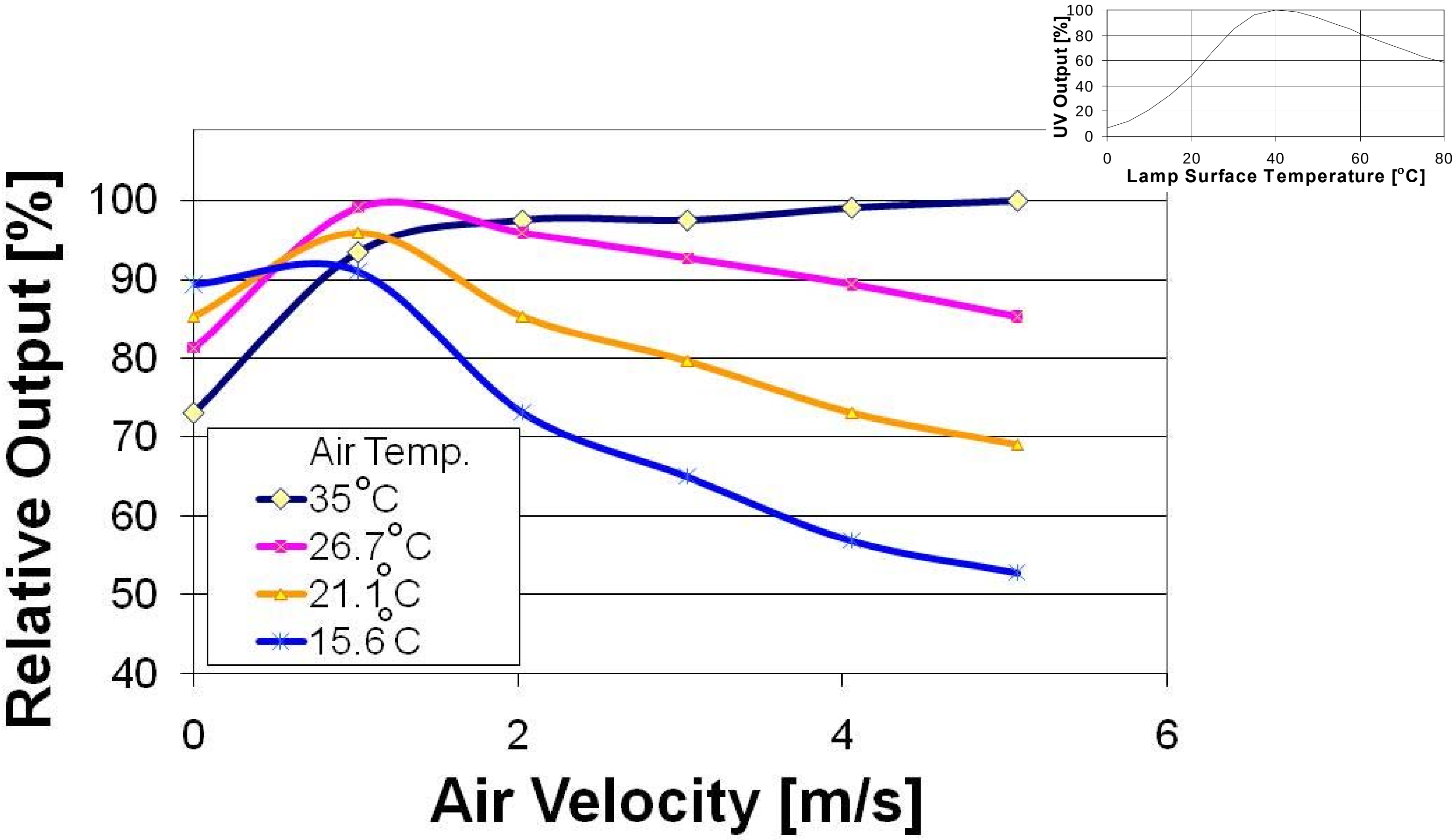
Center (flow left to right)



Socket end
(hot spot at cathode)

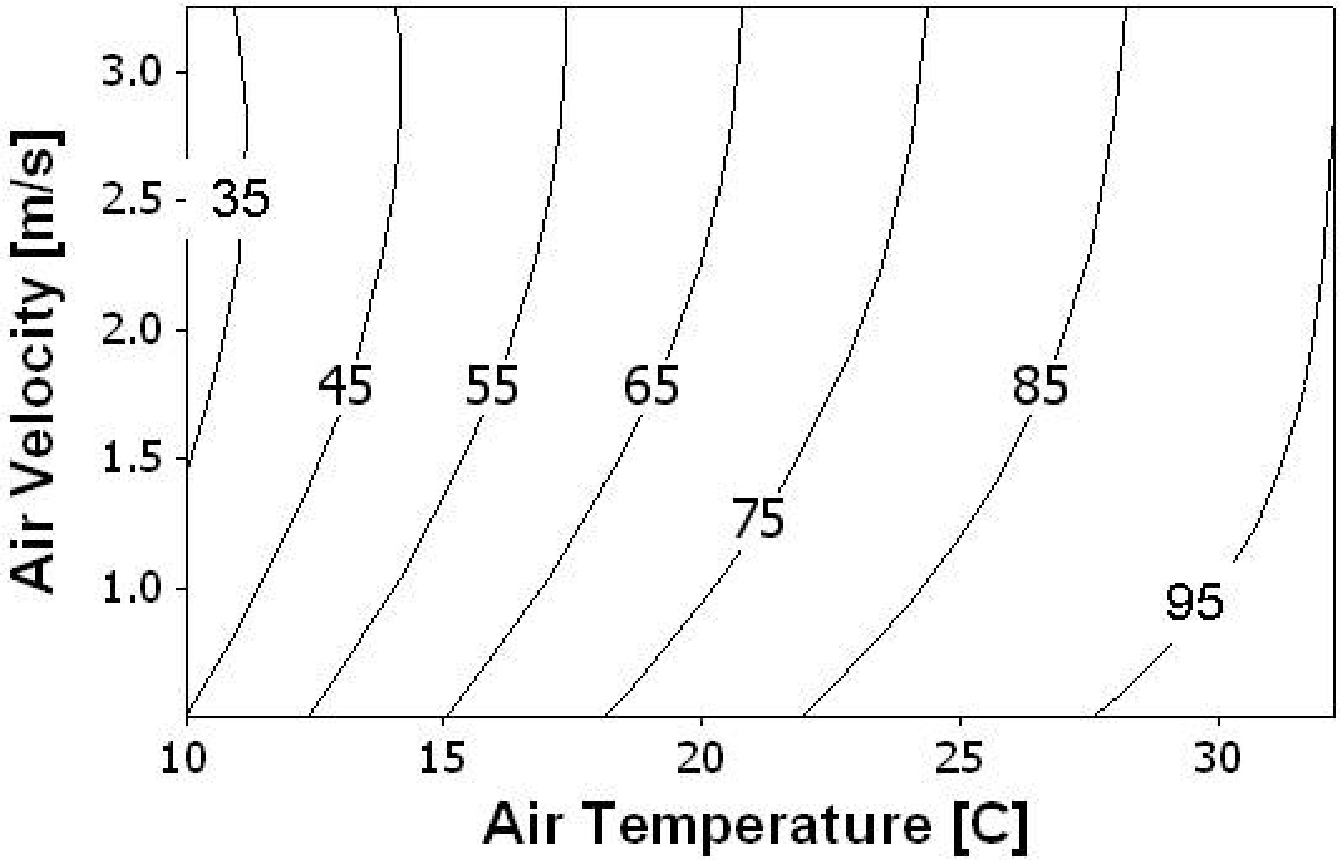
Effect of Air Temperature and Speed

(Standard output lamp, cross flow)

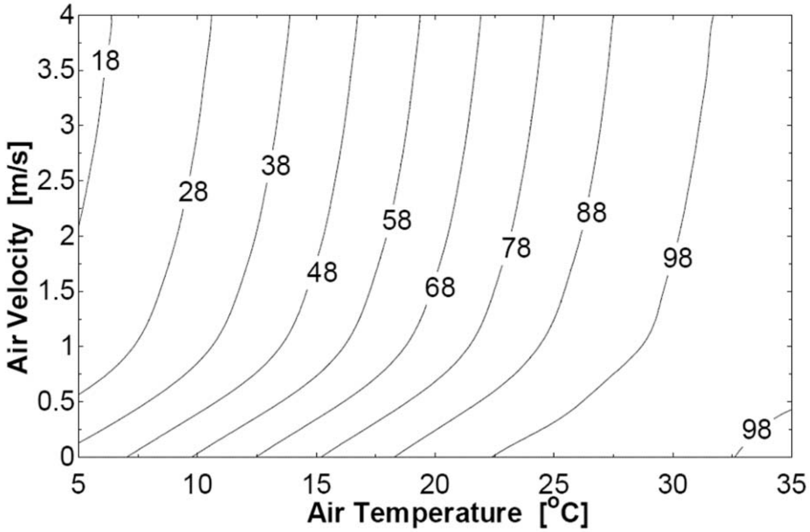


1 m/s = 196 ft/min, 15.6°C = 60°F, 35°C = 95°F

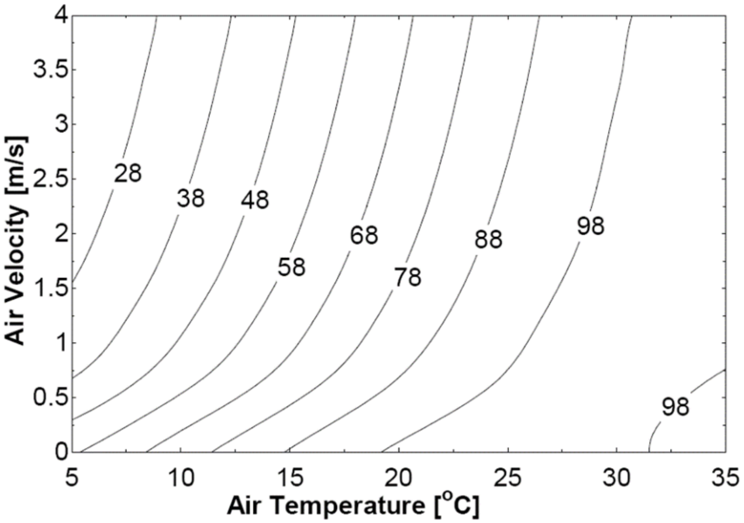
Lamp Wind Chill Map



Orientation Affects Wind Chill



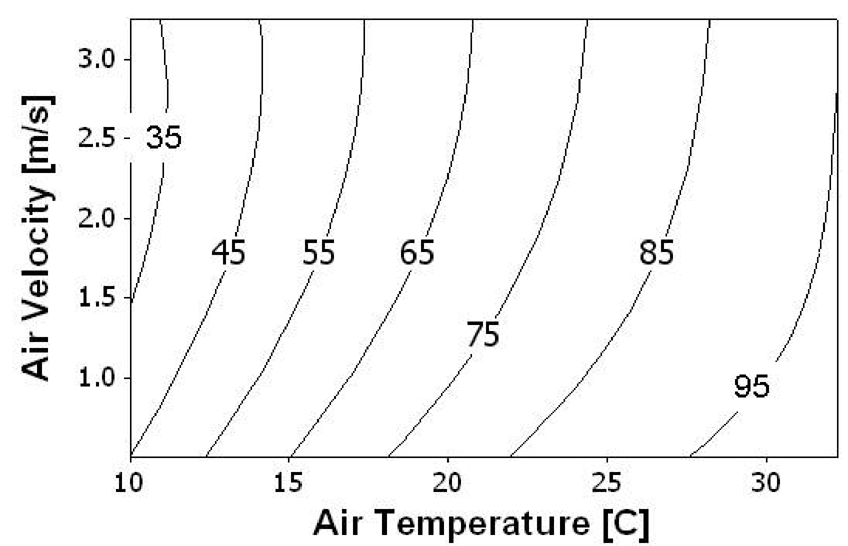
Cross flow to airstream



Parallel flow

Overall Lamp Output

- Factors
  - Depreciated output
  - Peak capacity adjusted for wind chill
- Example
  - Depreciation of 20%
  - 15°C, 2 m/s wind chill (59°F, 394 fpm) → ~55% max
  - Output = 0.80 × 0.55 = 44% of max



Humidity

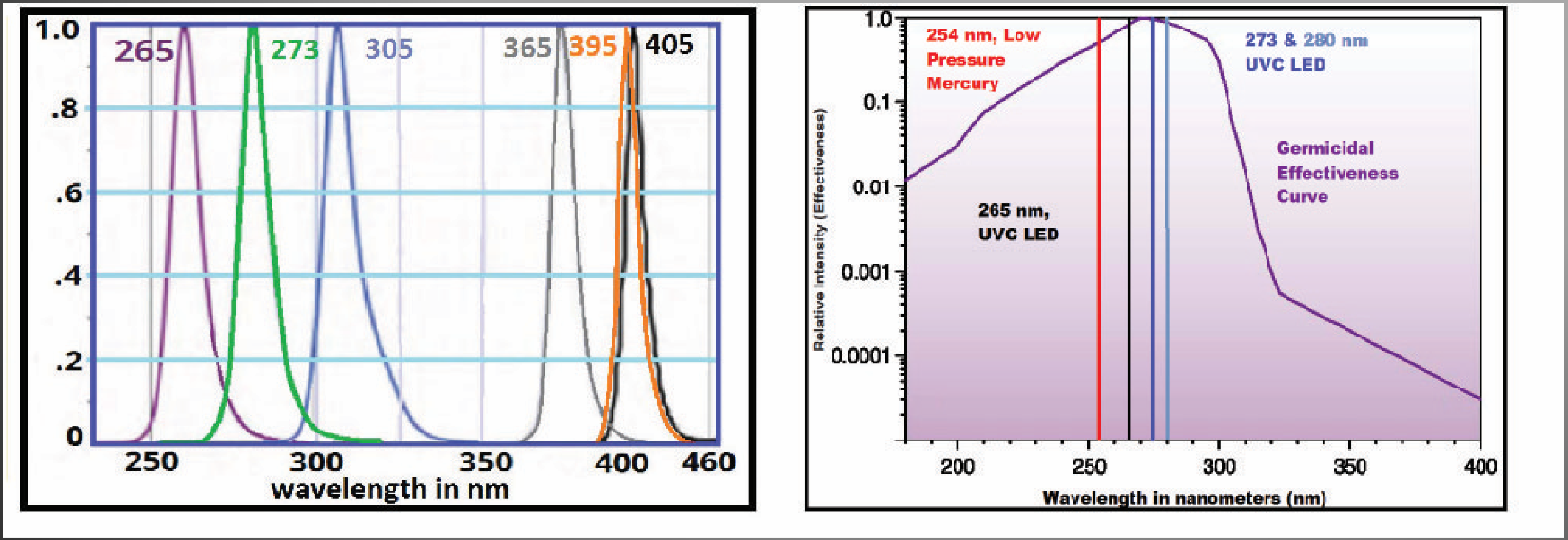
- Humidity affects microbial resistance (as seen previously)
- Effect on lamp performance is negligible
  - Air viscosity and conductivity effects – small
  - Optical path is generally short, so additional attenuation at high RH is also small

Emerging Technologies – LEDs

- LEDs should take over much of the market
  - Long life
  - Configuration flexibility
  - More wavelength options
  - Dimmable
  - Cyclable
  - Better in typical thermal environments
  - No mercury

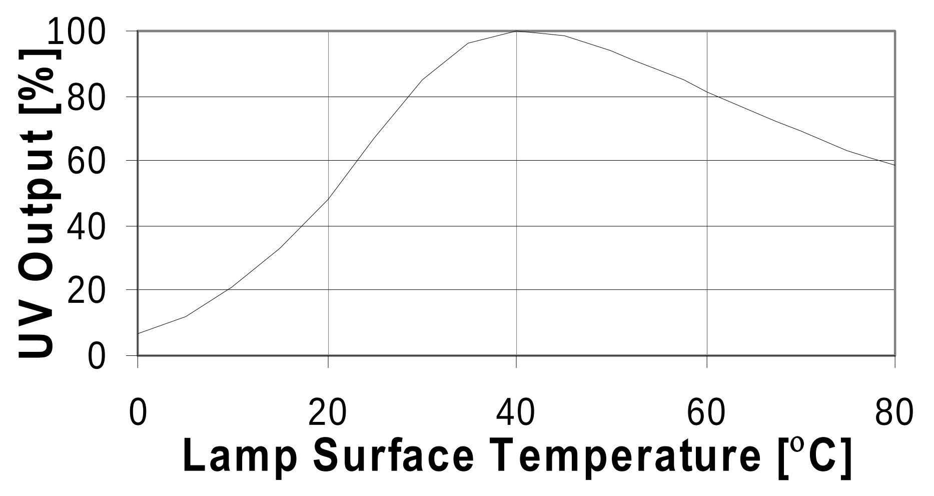
- Current market barriers
  - Low output (mW)
  - Cost
  - Durability
  - Standards

Emerging Technologies – LEDs

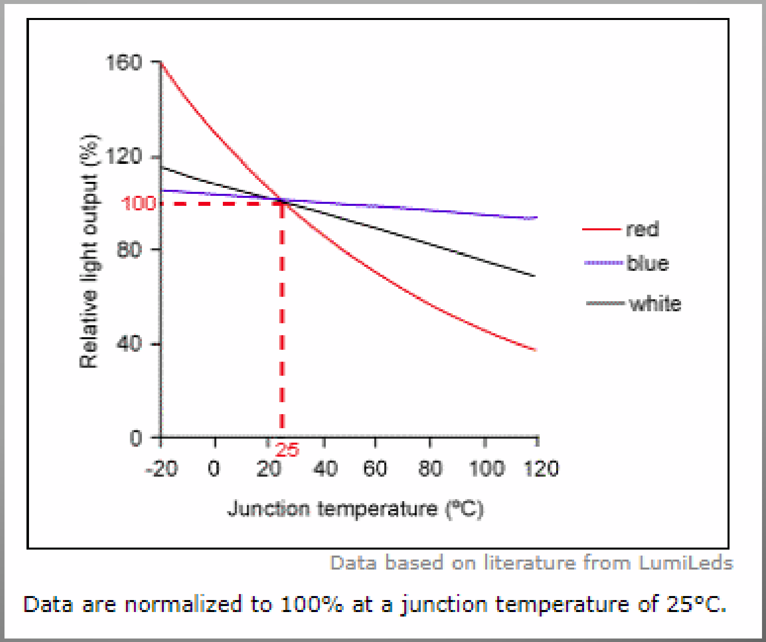


Source: International Light Technologies

Emerging Technologies – LEDs



Hg vapor lamp output vs. cold spot temperature



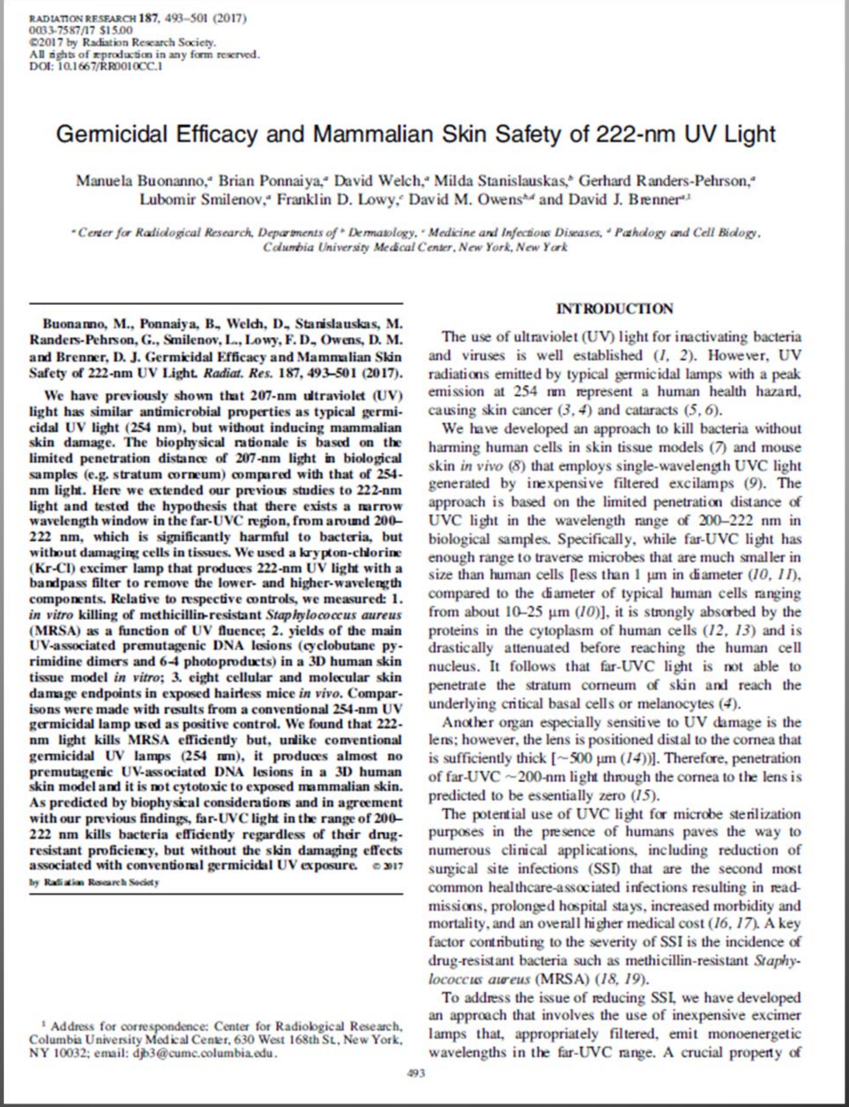
Data based on literature from LumiLeds

Data are normalized to 100% at a junction temperature of 25°C.

LED output vs. junction temperature

Emerging Technologies – Far UV

- Shorter wavelengths
- Good germicidal effectiveness
- Safe for human exposure
- Kr-Cl Excimer lamps produce ~222 nm UV-C



RADIATION RESEARCH **187**, 493–501 (2017)
0033-7587/17 $15.00

DOI: 10.1667/RR0010CC.1

Gemicidal Efficacy and Mammalian Skin Safety of 222-nm UV Light

Manuela Buonanno,[a] Brian Ponnaiya,[a] David Welch,[a] Milda Stanislauskas,[b] Gerhard Randers-Pehrson,[a]
Lubomir Smilenov,[a] Franklin D. Lowy,[c] David M. Owens[b,d] and David J. Brenner[a,1]

[a] *Center for Radiological Research, Departments of* [b] *Dermatology,* [c] *Medicine and Infectious Diseases,* [d] *Pathology and Cell Biology, Columbia University Medical Center, New York, New York*

Buonanno, M., Ponnaiya, B., Welch, D., Stanislauskas, M. Randers-Pehrson, G., Smilenov, L., Lowy, F. D., Owens, D. M. and Brenner, D. J. Germicidal Efficacy and Mammalian Skin Safety of 222-nm UV Light. ***Radiat. Res.*** **187, 493–501 (2017).**

We have previously shown that 207-nm ultraviolet (UV) light has similar antimicrobial properties as typical germicidal UV light (254 nm), but without inducing mammalian skin damage. The biophysical rationale is based on the limited penetration distance of 207-nm light in biological samples (e.g. stratum corneum) compared with that of 254-nm light. Here we extended our previous studies to 222-nm light and tested the hypothesis that there exists a narrow wavelength window in the far-UVC region, from around 200–222 nm, which is significantly harmful to bacteria, but without damaging cells in tissues. We used a krypton-chlorine (Kr-Cl) excimer lamp that produces 222-nm UV light with a bandpass filter to remove the lower- and higher-wavelength components. Relative to respective controls, we measured: 1. ***in vitro*** **killing of methicillin-resistant** ***Staphylococcus aureus*** **(MRSA) as a function of UV fluence; 2. yields of the main UV-associated premutagenic DNA lesions (cyclobutane pyrimidine dimers and 6-4 photoproducts) in a 3D human skin tissue model** ***in vitro*****; 3. eight cellular and molecular skin damage endpoints in exposed hairless mice** ***in vivo*****. Comparisons were made with results from a conventional 254-nm UV germicidal lamp used as positive control. We found that 222-nm light kills MRSA efficiently but, unlike conventional germicidal UV lamps (254 nm), it produces almost no premutagenic UV-associated DNA lesions in a 3D human skin model and it is not cytotoxic to exposed mammalian skin. As predicted by biophysical considerations and in agreement with our previous findings, far-UVC light in the range of 200–222 nm kills bacteria efficiently regardless of their drug-resistant proficiency, but without the skin damaging effects associated with conventional germicidal UV exposure.**

INTRODUCTION

The use of ultraviolet (UV) light for inactivating bacteria and viruses is well established (*1, 2*). However, UV radiations emitted by typical germicidal lamps with a peak emission at 254 nm represent a human health hazard, causing skin cancer (*3, 4*) and cataracts (*5, 6*).

We have developed an approach to kill bacteria without harming human cells in skin tissue models (*7*) and mouse skin *in vivo* (*8*) that employs single-wavelength UVC light generated by inexpensive filtered excilamps (*9*). The approach is based on the limited penetration distance of UVC light in the wavelength range of 200–222 nm in biological samples. Specifically, while far-UVC light has enough range to traverse microbes that are much smaller in size than human cells [less than 1 μm in diameter (*10, 11*), compared to the diameter of typical human cells ranging from about 10–25 μm (*10*)], it is strongly absorbed by the proteins in the cytoplasm of human cells (*12, 13*) and is drastically attenuated before reaching the human cell nucleus. It follows that far-UVC light is not able to penetrate the stratum corneum of skin and reach the underlying critical basal cells or melanocytes (*4*).

Another organ especially sensitive to UV damage is the lens; however, the lens is positioned distal to the cornea that is sufficiently thick [~500 μm (*14*))]. Therefore, penetration of far-UVC ~200-nm light through the cornea to the lens is predicted to be essentially zero (*15*).

The potential use of UVC light for microbe sterilization purposes in the presence of humans paves the way to numerous clinical applications, including reduction of surgical site infections (SSI) that are the second most common healthcare-associated infections resulting in readmissions, prolonged hospital stays, increased morbidity and mortality, and an overall higher medical cost (*16, 17*). A key factor contributing to the severity of SSI is the incidence of drug-resistant bacteria such as methicillin-resistant *Staphylococcus aureus* (MRSA) (*18, 19*).

To address the issue of reducing SSI, we have developed an approach that involves the use of inexpensive excimer lamps that, appropriately filtered, emit monoenergetic wavelengths in the far-UVC range. A crucial property of

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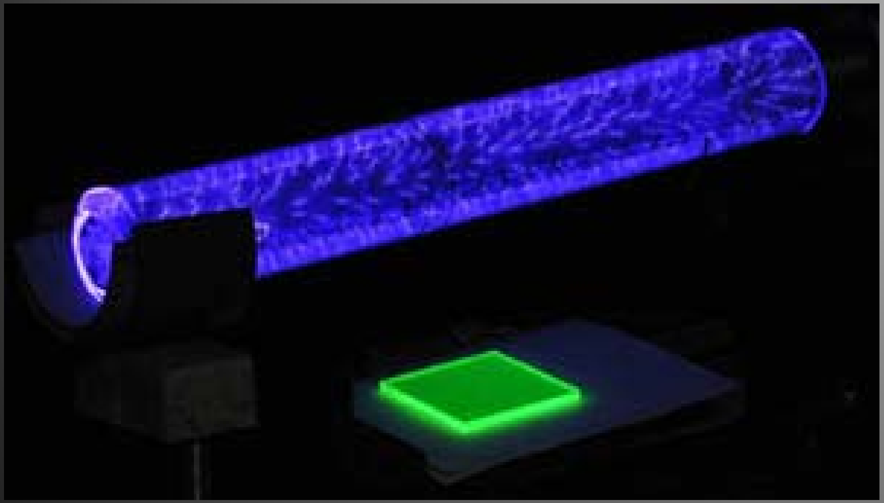
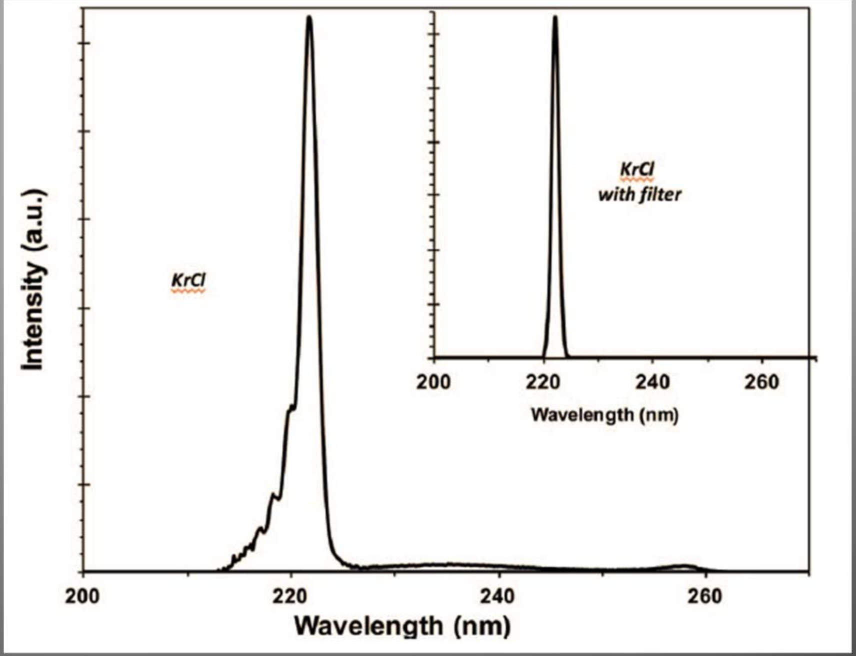
Emerging Technologies – Far UV



Institute of High Current Electronics SB RAS



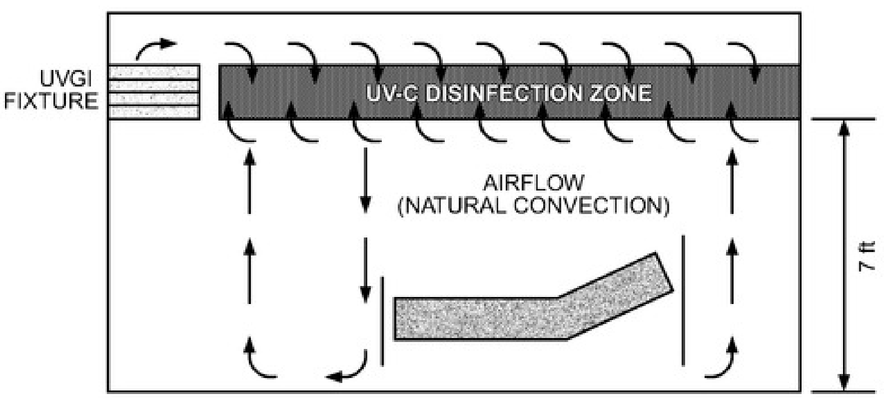
Kr – Cl excimer lamp
Buonanno, et al. (2017)

UVGI Applications and System Design Principles

- Upper-Air Disinfection
- In-Duct Surface Disinfection
- In-Duct Air Disinfection
- In-Room Surface Disinfection

Upper-Air Disinfection

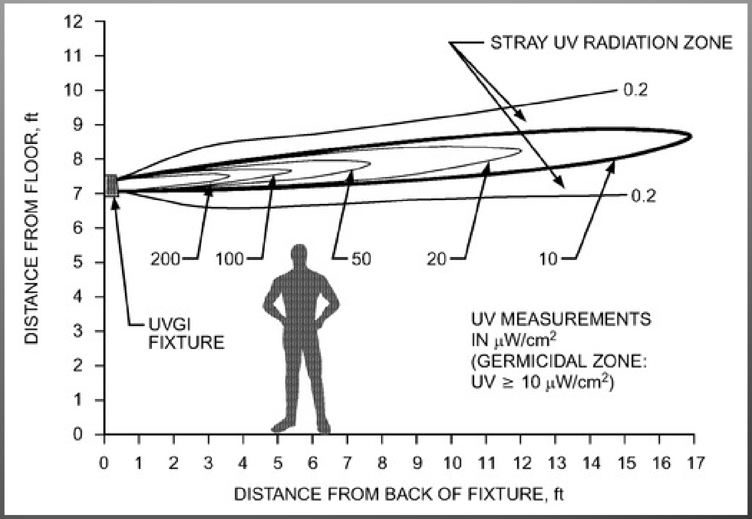
- Fixtures located above occupied zone
- Fixture directs UVC horizontally to create a disinfection zone
- Natural or forced air movement brings contaminated air into zone



ASHRAE Handbook – 2019 HVAC Applications, Ch. 62, Fig. 5

Upper-Air Disinfection

- Air distribution system not required, but good mixing ventilation helps
- Safety a concern because lamps are in occupied space
- Test for acceptable occupied zone exposure



2019 *ASHRAE Handbook—HVAC Applications*, Ch. 62, Fig. 6

Upper Room Air Disinfection

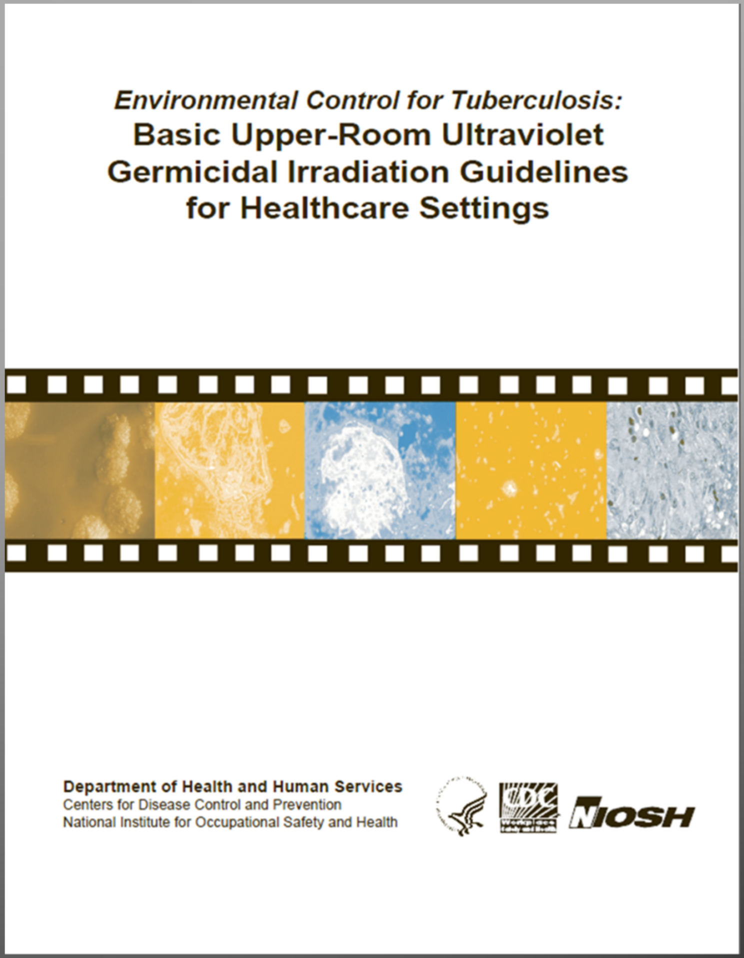
Upper-Air Disinfection

- Oldest type of air disinfection system
- Good application for standard lamps
- Approved by U.S. Centers for Disease Control/ National Institute for Occupational Safety and Health for control of tuberculosis
- NIOSH (2009): *Environmental Control for Tuberculosis: Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for Healthcare Settings*

http://www.cdc.gov/niosh/docs/2009-105/pdfs/2009-105.pdf

NIOSH (2009) Upper-Air Design Guidelines

- Irradiance
  - Arrange lamps for uniform irradiance
  - 30 $\mu W/cm^2$ to 50 $\mu W/cm^2$ average
  - Suggested simplification
    - 1.87 W/m^2 (0.17 W/ft^2) of lamps for floor area
    - 6 W/m^3 (0.18 W/ft^3) of lamps for upper zone volume



Environmental Control for Tuberculosis:
Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for Healthcare Settings

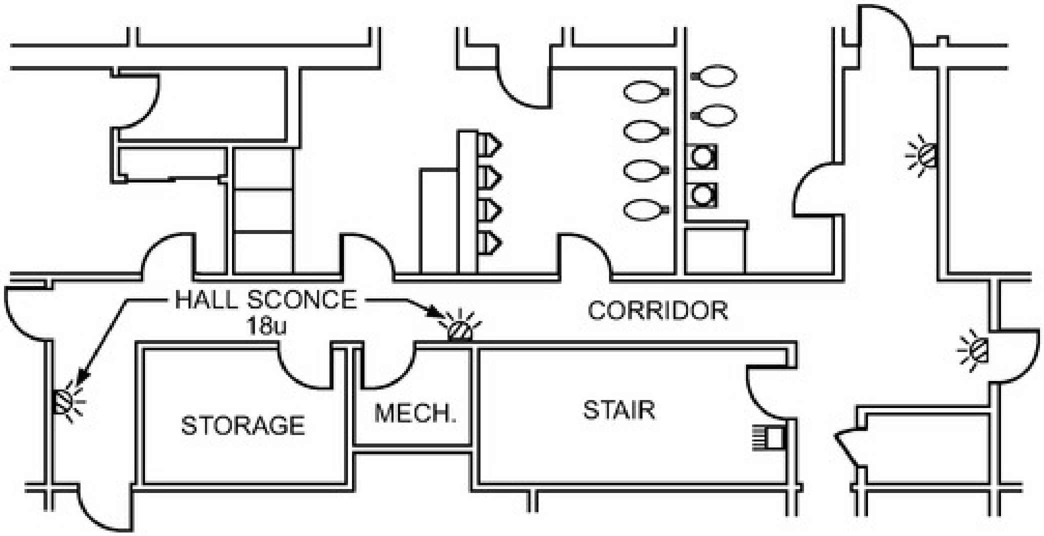
Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

NIOSH (2009) Upper-Air Design Guidelines

- Ventilation
  - Mixing preferred
  - Additive to 6 ach
- Humidity: <60% RH

Upper-Air System Design

- Older guideline for sizing (First, Nardell, *et. al*, 1999)
  - 30 W of input power per 200 ft^2 (19 m^2) of floor area; i.e., 0.15 W/ft^2 or 1.58 W/m^2—very similar to NIOSH
- Key is getting good air distribution, uniform irradiance distribution



Upper-Room UVGI Fixtures with 180° Emission Profile Covering Corridors Originally published in *Public Health Reports* (Brickner et al. 2003)

Upper-Air System Design

- Irradiance distribution is critical
- UVC irradiance distribution
  - Measurements
  - Calculation
    - View factor
    - Ray tracing

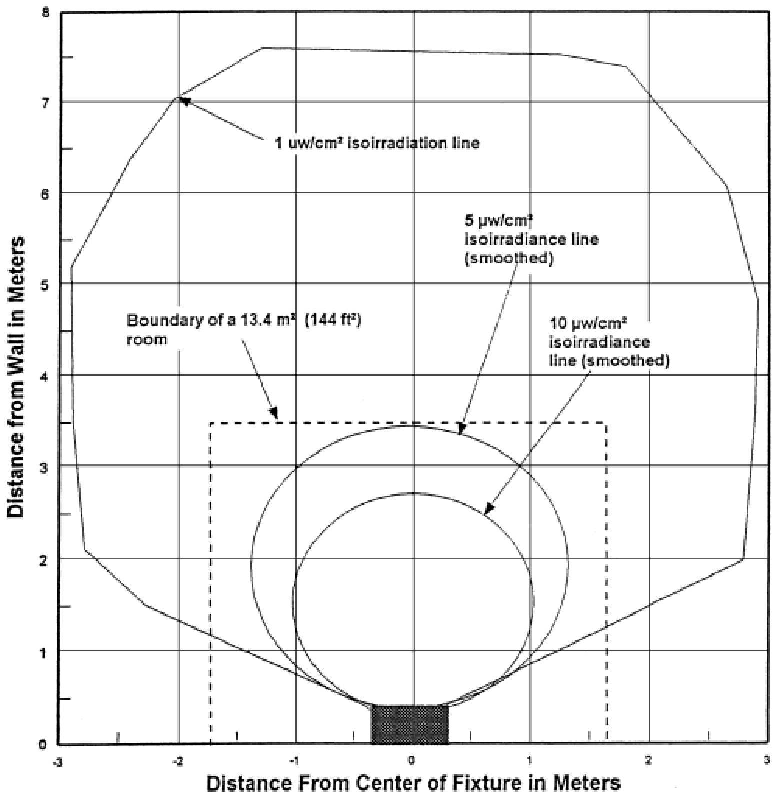


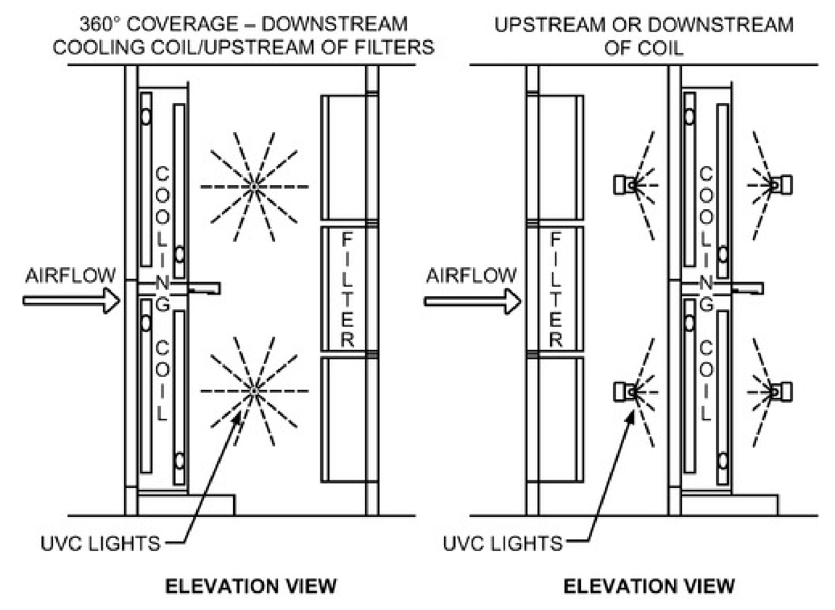
Figure 1 *Emission from a wall-mounted fixture with closed sides containing two 9 W lamps.*

In-Duct Surface Disinfection

- Irradiate coil or filter surfaces to control growth—upstream/downstream/both
- Reduces air-side flow resistance, increases heat conductance
- GSA P100 (2018 ed., 5.1, 5.2.6)
  - "Tier 3 High Performance" systems
  - Required for cooling coils, condensate pans, and other wetted AHU surfaces
- Wide range of opinions on sizing:
  - 5 $\mu W/cm^2$ on opposite side of coil
  - 200–2000 $\mu W/cm^2$ on irradiated face

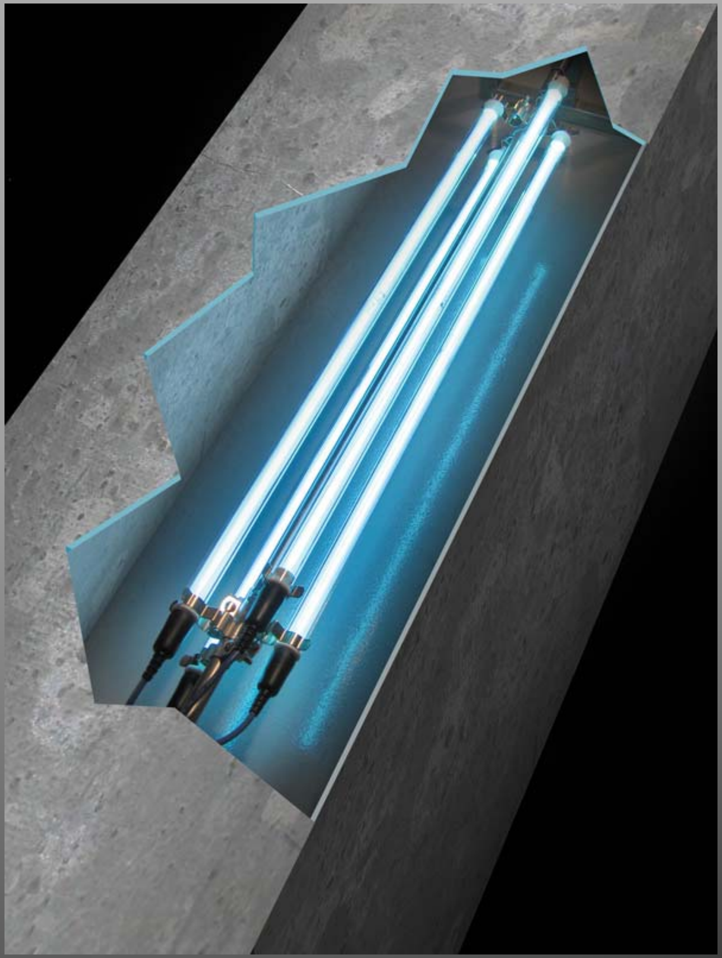
In-Duct Surface Disinfection

- Multiple choices for lamp configuration
  - Downstream
  - Upstream
  - Both
- Considerations:
  - Irradiate condensate pan
  - Treat coil and filter bank
  - Impact of air temperature on lamp output



In-Duct Air Disinfection

- Deactivate airborne microorganisms “on the fly”
- Typically installed in AHU and do dual coil/ filter cleaning duty
- Sizing of dual systems dictated by air disinfection requirements



Commercial In-Duct

Downstream coil surface/air installation

Residential In-Duct

In-Duct Air Disinfection Design

- Factors that affect design:
  - Design scenario
    - Design microorganism or generic *k*
    - Performance goal
  - UVGI location in HVAC system
    - Airflow rate
      - Velocity
      - Residence time
    - Air temperature
  - Exposure zone
    - Dimensions
    - Reflectivity
  - Lamp/ballast options
  - Lamp configuration

In-Duct Air Disinfection Design

- Process
  - Establish design scenario
  - Determine UV-C dose
  - Identify equipment selections that deliver design dose for candidate locations and conditions (work with manufacturer)
  - Evaluate energy use, cost, and possibly outcome
  - Select best system based on performance, economics, and other criteria

In-Duct Air Disinfection Design

- Performance goals for UVGI systems
  - Specified design single-pass efficiency is typical
    - Methods to determine “design” conditions vary greatly
    - Single-pass efficiency (1-S) does not directly indicate the effect of the system on occupied zone conditions
  - Other possible metrics:
    - Airborne concentration
    - Exposure dose
    - Sick days/lost productivity

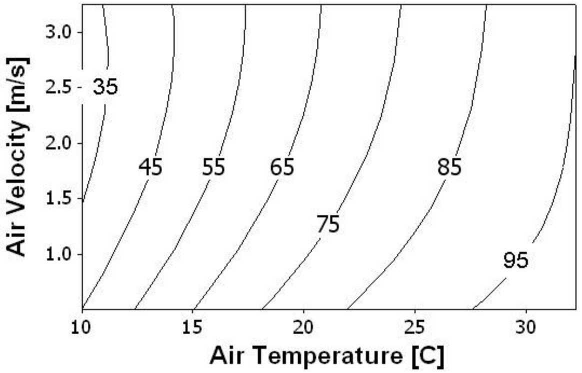
In-Duct Air Disinfection Design

- Design conditions
  - Design dose achieved at…
    - Uncorrelated worst-case velocity and temperature (may be more extreme than actual worst case)
    - Actual worst case velocity/temperature combination
    - Statistically extreme conditions
      - For example, dose not achieved 5% of time
      - "85% single-pass inactivation for 5th percentile conditions"
  - Choice of UVGI location and approach to design temperature and velocity affects lamp power required
    - Wind chill
    - Residence time

In-Duct Air Disinfection Design

- Power required for design dose depends on wind chill and residence time effects:

$$\left(\frac{P}{P_{ref}}\right)_{\substack{Equal\\Dose}} = \frac{LampOutput_{\%max,ref}}{LampOutput_{\%max}} \cdot \frac{V}{V_{ref}}$$

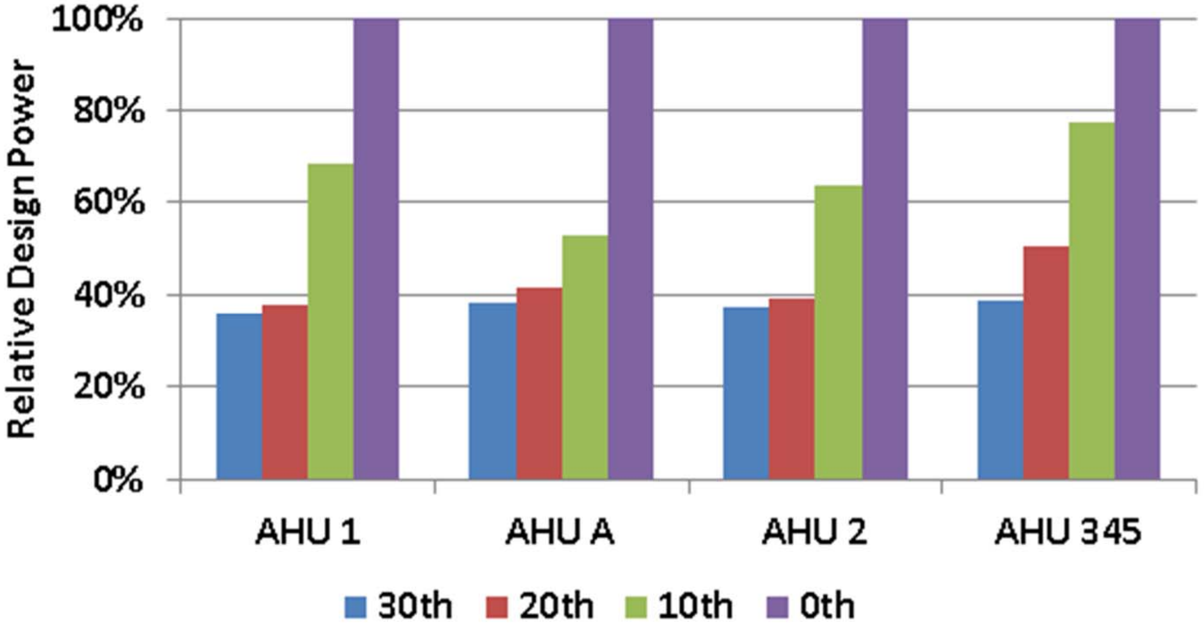


- Ex.: 15C/1.5 m/s reference vs. 20C/2.0 m/s

$$\frac{P}{P_{ref}} = \frac{53\%}{64\%} \cdot \frac{2.0\, m/s}{1.5\, m/s} = 0.828 \cdot 1.333 = 1.10$$

In-Duct Air Disinfection Design

Design percentile has strong effect on lamp power requirement



Relative power requirement for 85% inactivation at different design percentiles

In-Duct Air Disinfection Design

- Determination of lamp power required typically requires manufacturer input
- Dose can be estimated by software based on radiation view factor methods or by ray tracing
- Some manufacturers have proprietary software for evaluating configuration options

In-Duct Air-Distribution Design

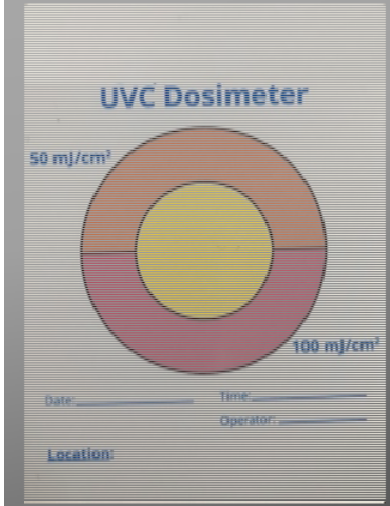
- Cycle lamps or modulate capacity?
  - Cycling saves energy, reduces lamp life
  - Modulation adds cost for dimming or switching and may require UV measurement for feedback
  - Many systems operate continuously
- For air-handler installation, upstream or downstream of coil, or both?
  - Downstream irradiates condensate pan, but environment may require more lamp power
  - Upstream may permit irradiation of coil and filters and provide better lamp environment
  - Upstream air disinfection (high power) + downstream coil treatment (low power) may be best

In-Room Surface Disinfection

- Permanently installed fixtures
- Healthcare application
- May have occupied/unoccupied modes

In-Room Surface Disinfection

- Standalone, portable
- May have ability to sense dose delivered
- Otherwise, use dosimeters



Self-Contained Air Disinfection

- Lamps and fan in a module
- May have high single-pass inactivation, but effectiveness depends on ability to recirculate space

Self-Contained Air Disinfection – Portable

- Lamps in enclosure
- Fan – 450 /1000 cfm (212 / 472 L/s)
- Filtration can be added

Economics of UVGI Technologies Applied to HVAC Systems

- Typical Upper-Air Costs
- Typical In-Duct Costs
- Coil Surface Disinfection Costs
- Life-Cycle Cost

Economic Analysis of UVGI

- First cost: equipment and installation
- Operating cost
  - Energy cost
    - Electric power to lamps
    - Increased cooling load
    - Decreased heating load
    - Increased fan power
  - Lamp replacement and other maintenance
- Benefits
  - Health and productivity
  - Energy savings relative to alternative technologies

Upper-Air Costs

- Using Riley, *et al.*, rule of thumb: 30 W per 200 ft^2
- Typical fixture 36 W (12 W UV)
- Equipment cost \$3 – 4/ft^2
- Installation cost can vary widely – 0.5 – 2 hrs. per fixture at electrical contractor rates of \$75 -100/hr.
- Operating cost: \$0.13/ft^2 · yr. for continuous operation @ \$0.10/kWh

In-Duct Costs

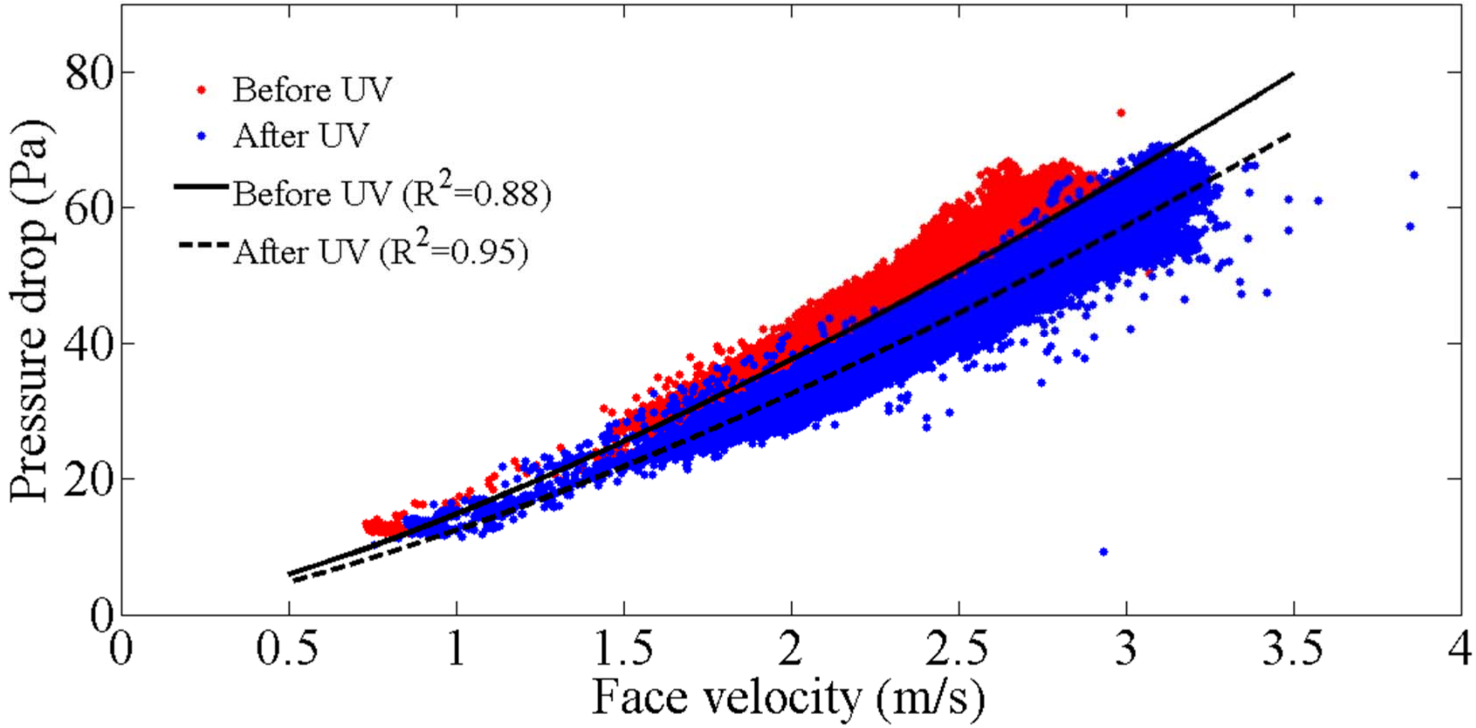
- Typical air/coil system
  - $0.10 – $0.25/cfm equipment cost
  - At $0.10/kWh, annual cost for continuous operation ~$0.018/cfm, also $0.018/ft^2
  - Clearance for 0.25 s exposure @ 500 fpm is ~2 ft
  - Full flow temperature rise ~0.06°F

Coil Surface Treatment Economics

- Montgomery and Baker (*ASHRAE Journal,* November 2009)
  - ~10% – 15% HVAC efficiency improvement possible for clean vs. dirty coils
  - Not specific to UVGI
- Keikavousi (*Engineered Systems*, February 2004)
  - Badly fouled nominal 6000 cfm unit in Orlando FL,
  - ~$2000 installation cost, estimated $4900 annual savings
- Firrantello and Bahnfleth (ASHRAE RP-1738, 2017)
  - Simulation based on field measurements and Keikavousi's article
  - 0.5%-4.5% reduction in HVAC energy use—mostly fan energy
  - Significant collateral air quality benefit, reduce need for mechanical cleaning
  - Median benefit including IAQ benefit ~$0.15/sf NPV vs. $0.51/sf cost for conventional cleaning…depends on many parameters
- Yi, Sekhar, Bahnfleth, Cheong, Firrantello (2016, 2017)
  - Simulation based on measurements in Singapore laboratory
  - Energy savings and maintenance cost savings can result in net economic benefit

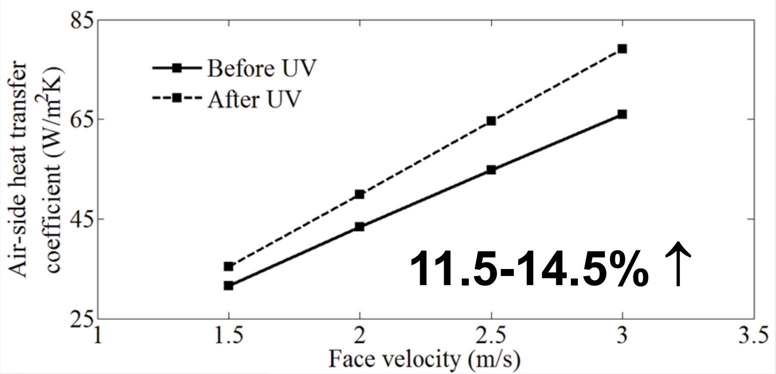
Yi, et al.—Δ*P* Reduction up to 15%

Singapore Laboratory

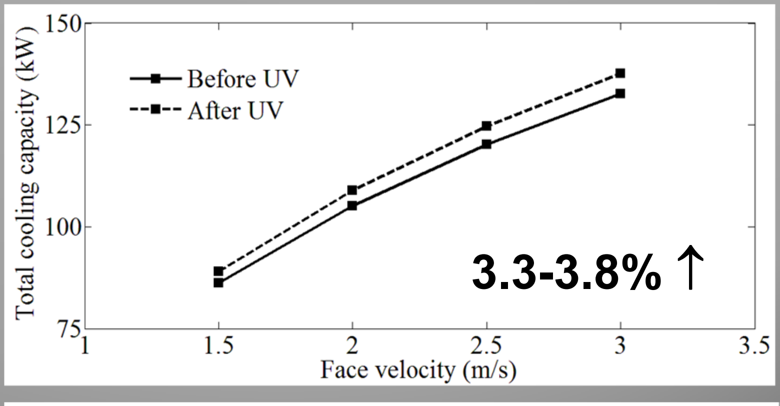


Yi, et al.—Heat Transfer Benefits

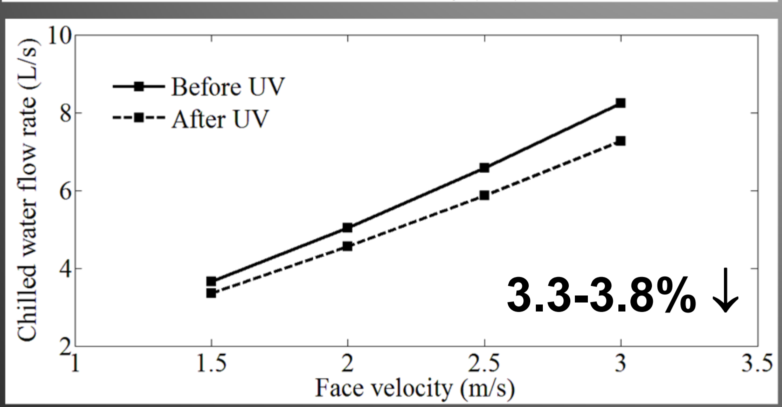
Singapore Laboratory



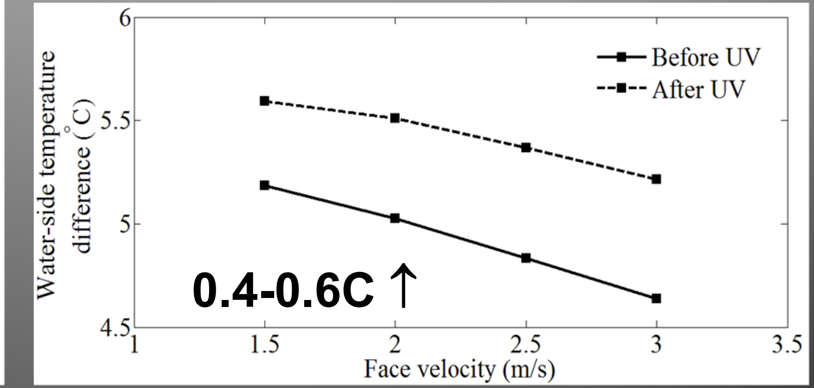
11.5-14.5% ↑



3.3-3.8% ↑



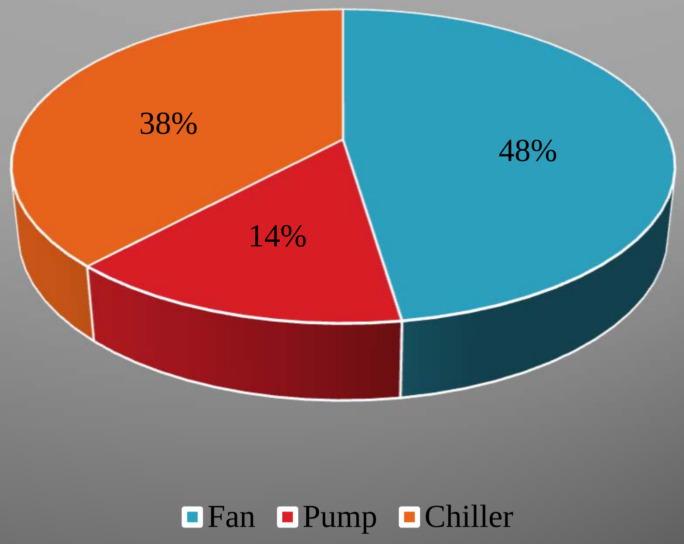
3.3-3.8% ↓



0.4-0.6C ↑

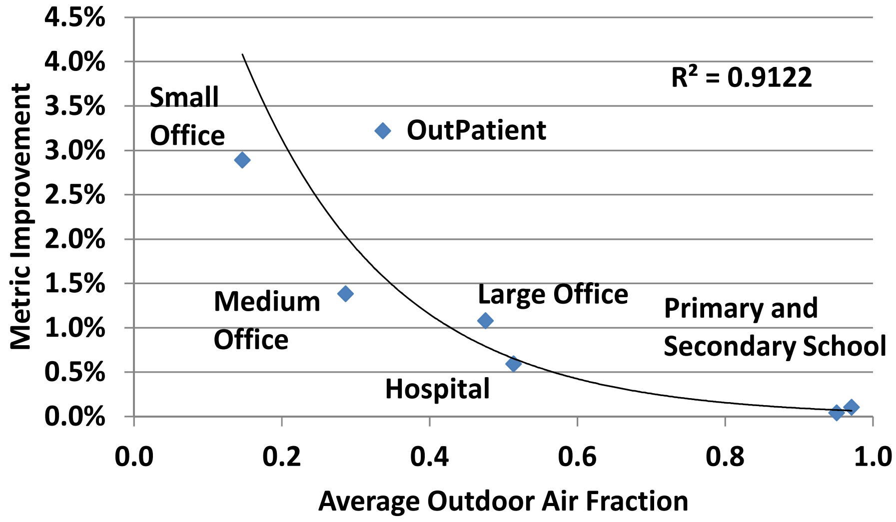
Yi, et al.—Annual Energy Impact

- Apply experimental results to EnergyPlus models
- Singapore:
  - Fan energy ↓ 9.1%
  - Pump energy ↓ 6.2%
  - Chiller energy ↓ 0.41 %
- Energy and economic impact vary with climate and occupancy



Collateral IAQ Impact—Modeling

- Wells-Riley equation
- Metrics varied with occupancy—HAI incidence, absentee rate, DALY…
- Larger than energy and maintenance cost savings
- Benefit sensitive to system effects



Bahnfleth and Firrantello (2017)

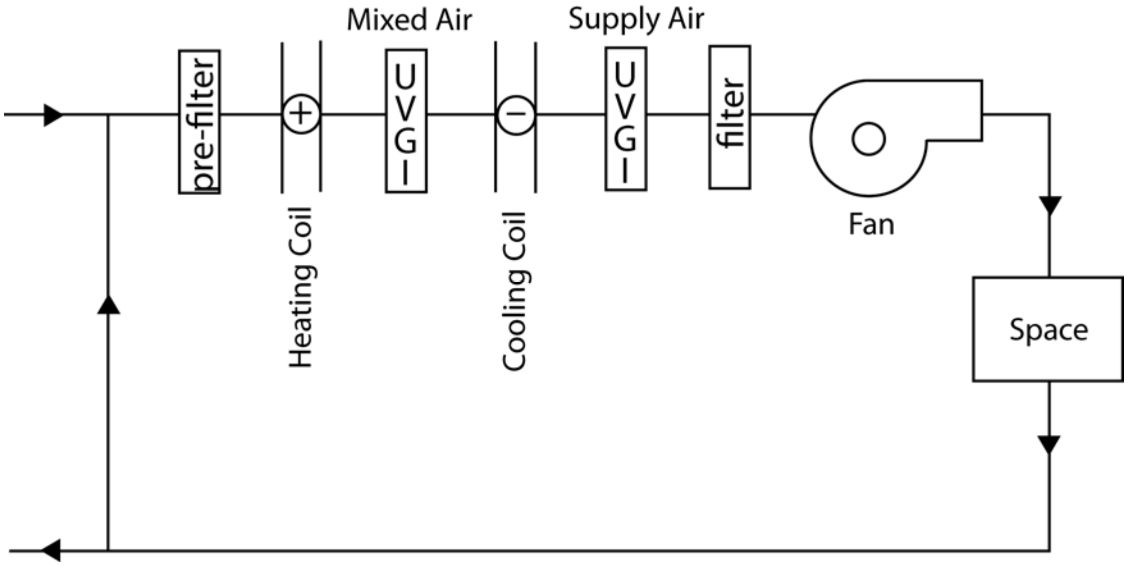
Simulation-Based LCC Analysis of In-Duct Air Disinfection vs. Filtration

- Lee and Bahnfleth (2013)
- Performance simulation
  - Thermal/energy (whole-building—eQUEST)
  - IAQ control (components, system—custom MATLAB)
- Economic analysis
  - First-cost
  - Annual labor and equipment cost
  - Energy cost (direct/indirect)
  - *Benefit?*

If benefit cannot be quantified with sufficient accuracy, an alternative approach is to compare with cost of alternative methods (e.g., filtration, dilution) to achieve the same level of contaminant control

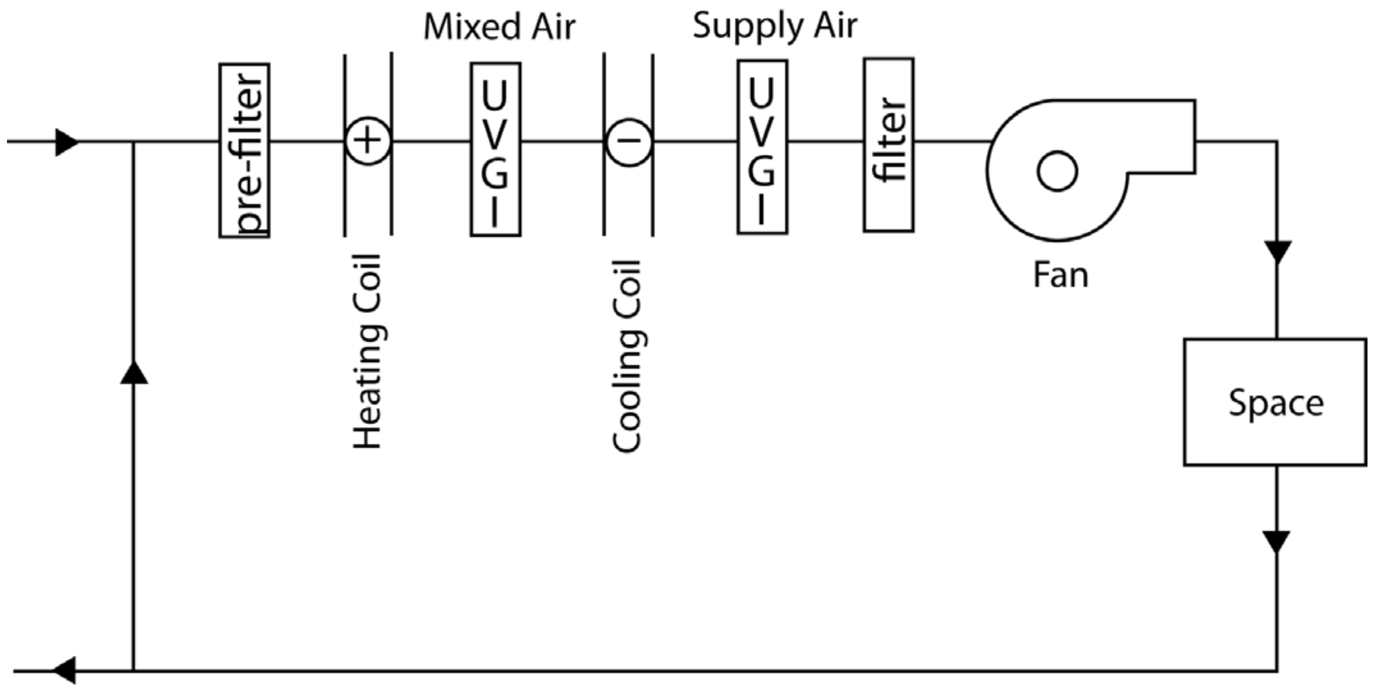
Example–Office Building

- New York City
- 4 floors @ 2380 m^2 (25,600 ft^2)
- 1 VAV system/floor
  - 8 m^3/s (17,000 cfm) SA, 10°C (50°F) SAT, 2.5 m/s (472 ft/min) face velocity, 1.8 m^3/s (3800 cfm) OA
  - MERV 6 filtration (base)



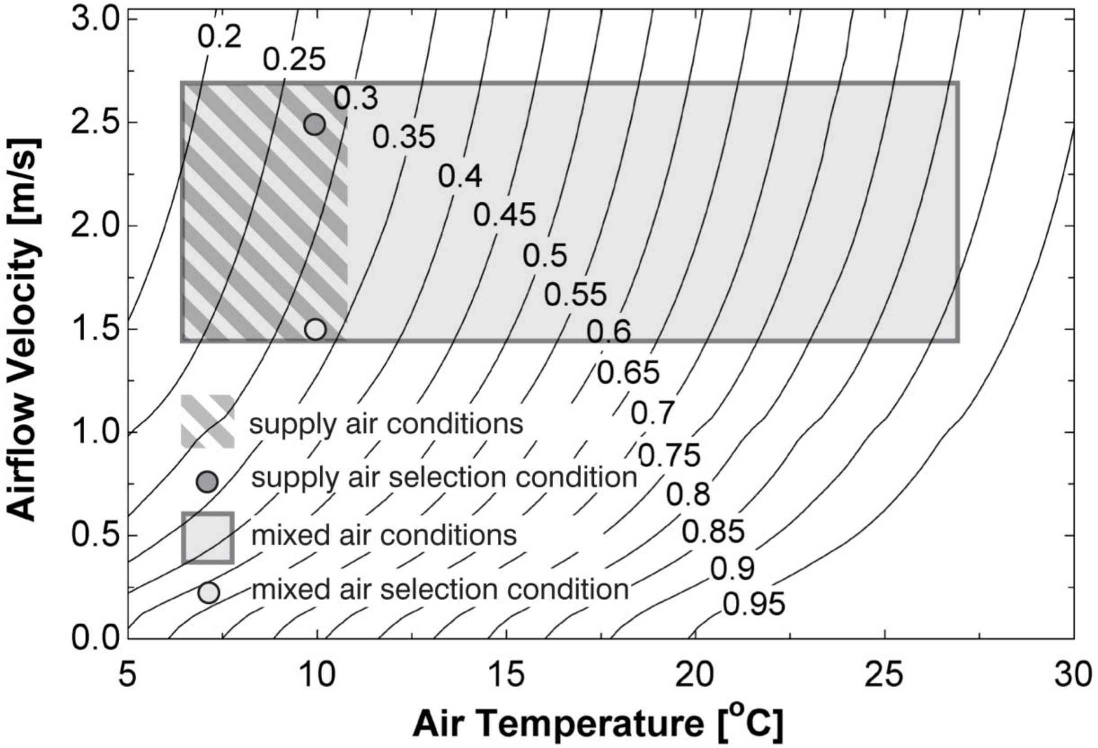
Study Cases

- Base HVAC system (minimum OA, MERV 6) + UVGI downstream of cooling coil
- Base HVAC system + UVGI upstream of cooling coil
- Base HVAC system + filtration equivalent to UVGI (MERV 12)



UVGI System Parameters

- Size for worst-case 85% inactivation of *S. aureus*
  - $k = 0.0035\ \text{cm}^2/\mu\text{J}$
  - $d = 1\ \mu\text{m}$ (η_f = 15%, 82%, 90% for MERV 6, 12,13)
  - Constant source during business hours (0900 – 1700)
- Philips TUV PL-L 60W HO lamps in cross flow, modelled per Lau, *et al.* (2009)

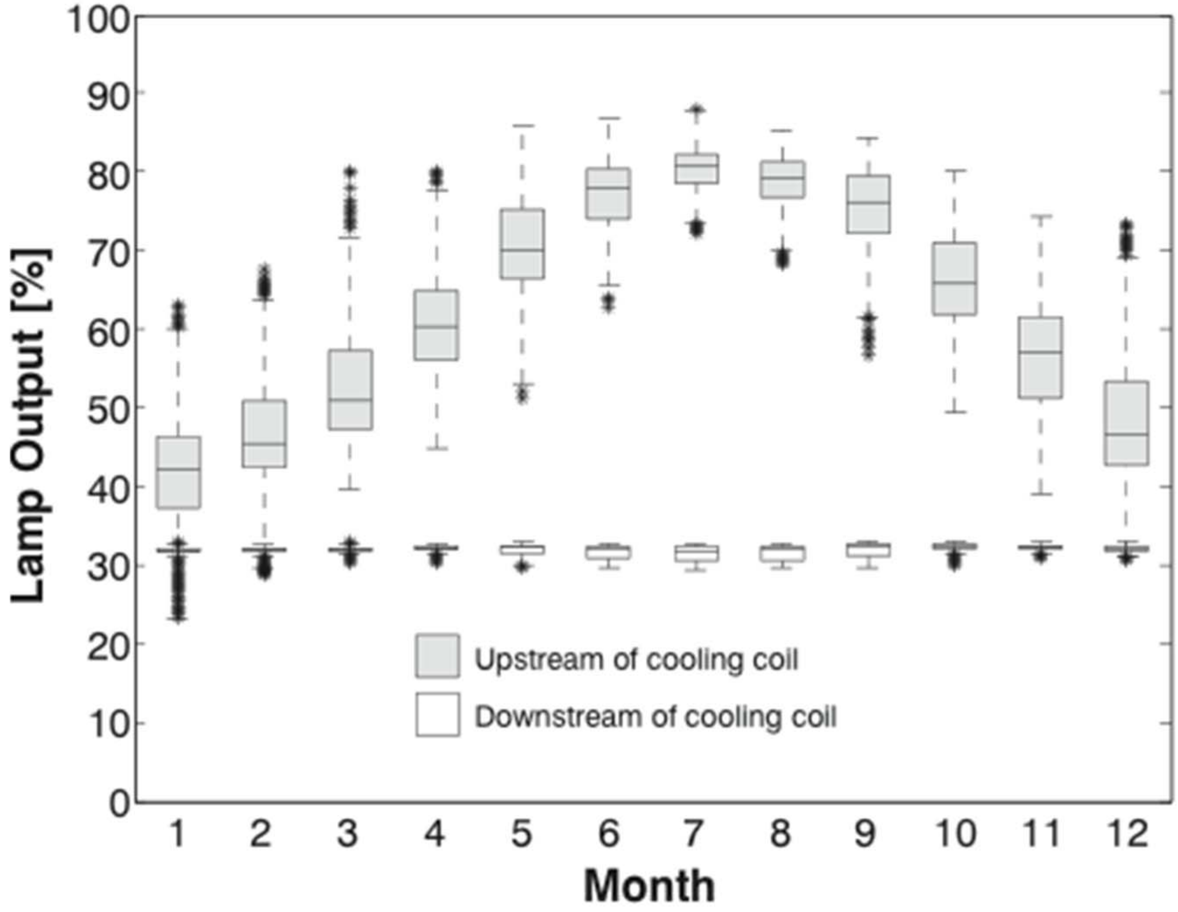


Results—UVGI Selection

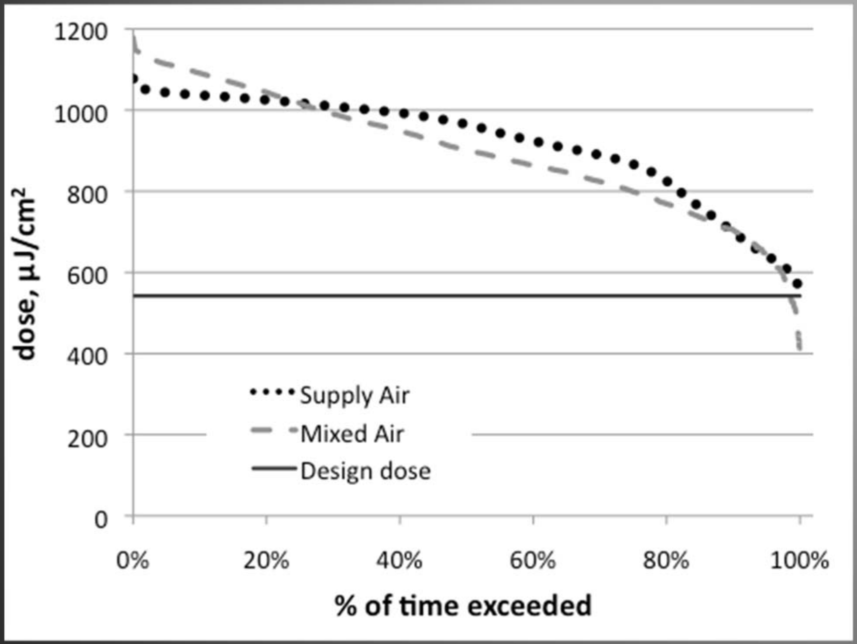
- Required dose: 542 µJ/cm^2
- Input power required depends on location
- Supply air is colder, causes greater derating of lamp

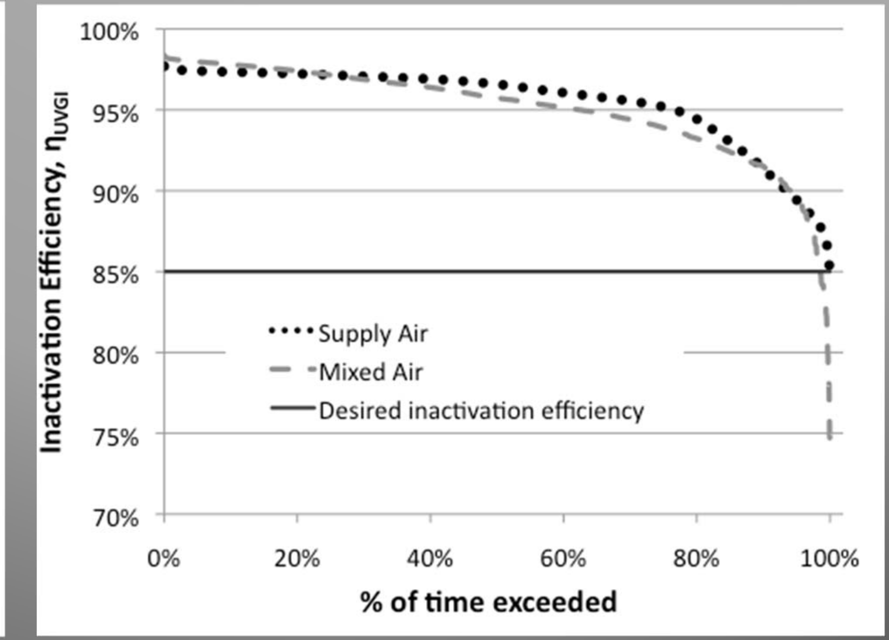
	Supply Air	Mixed Air
Temperature, ˚C (˚F)	10 (50)	10 (50)
Velocity, m/s (fpm)	2.5 (500)	1.5 (300)
Exposure time (s)	0.3	0.5
Lamp Output (%)	27.8	32.9
Irradiance (µW/cm^2)	6499	3295
Input power (W)	718	364

Results—Annual Lamp Output Variation



Results—Annual Dose and UVGI Efficiency





- Inactivation efficiency varies less than dose due to exponential nature of disinfection process

- Inactivation efficiency is >95% almost 80% of the time, much higher than design

UVGI Economics

- First cost and operating cost of IAQ control equipment can be estimated reasonably well
- Benefits of good IAQ are not well quantified
  - 10,000 m (30,000 ft) view: \$24–\$69 billion (2020) per year impact in U.S. (Fisk 2002)
  - Detailed models based on uncertain dose-response models and cost assumptions (Fisk, *et al*. 2005)
- Application of IAQ technology is limited by underdeveloped economic case

UVGI Economics

- Costs
  - Initial costs: design, installation of fixtures, initial lamping
  - Recurring costs: lamp replacement, cleaning
  - Energy cost: lamps, heating/cooling, fan
- Sizing affects all of the above

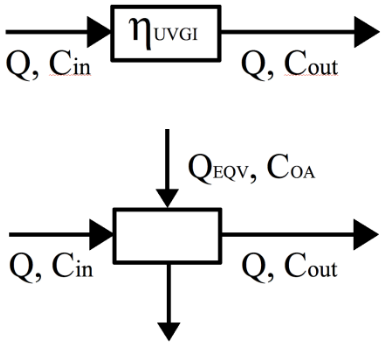
Economic Parameters

- UVGI equipment
  - $10/input W initial installed cost
  - $1/input W annual maintenance and lamp replacement
  - Continuous operation (8760 hrs/yr)
- Enhanced filtration
  - MERV 12: $1650/face m^2 ($15/ft^2) initial cost, $220/face m^2 ($20/ft^2) per replacement, change every 6 months
  - 250 Pa (1 in H_2O) additional pressure drop
- Electric power
  - $0.10/kWh
- Discount rate
  - 3% real rate

Health Benefit Estimate

- Based on Wells-Riley equation
  - Probability of infection related to air-change rate, α_v
  - Compute equivalent UVGI air change rate, α_{UVGI}
  - Relative risk impact calculated following Fisk, *et al.* (2005), including filtration and dilution
- Costs
  - \$200/person day average sick leave rate
  - 2% base sick leave rate
  - 5 person/93 m^2 occupant density

$$P = 1 - \exp\left[-\frac{ipqt}{Q}\right] = 1 - \exp\left[-\frac{ipqt}{\cancel{V}}\Big/\alpha_v\right]$$



$$\alpha_{UVGI} = \frac{Q_{UVGI}}{\cancel{V}}$$

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

Results–Energy Use and Cost

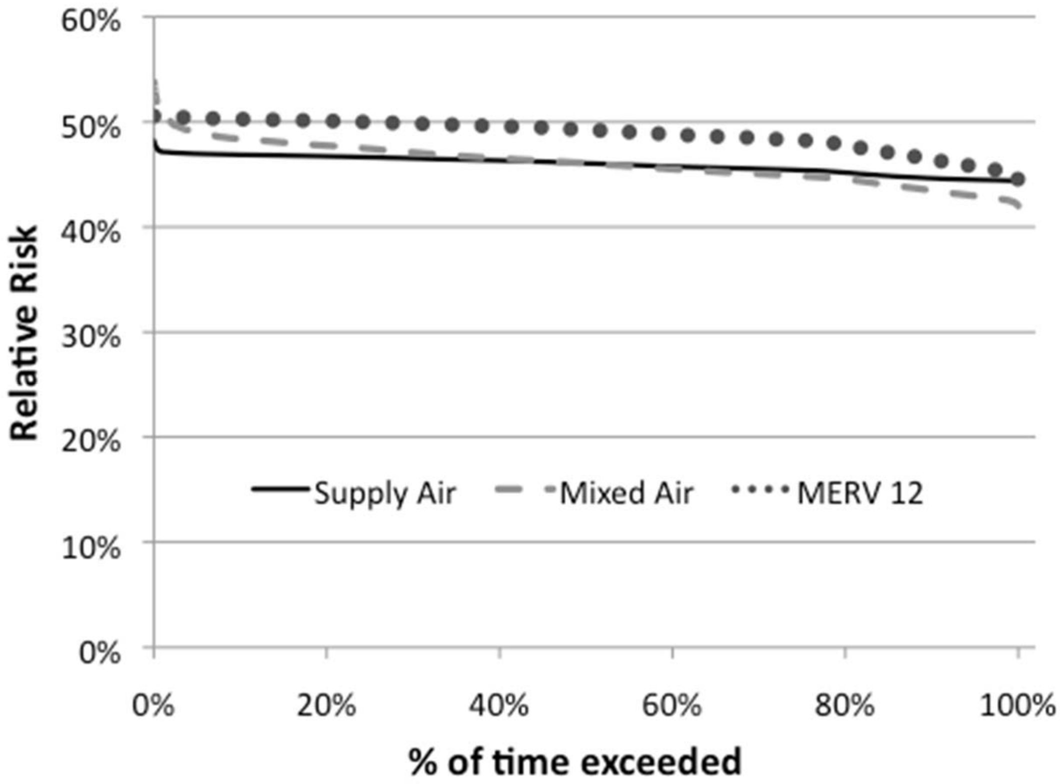
Annual Energy Consumption	UVGI @ SA	UVGI @ MA	MERV 12 Filtration
Power to lamps (kWh)	6290	3189	–
Cooling (kWh)	1175	575	9975
Fan (kWh)	400	200	17175
Heating-electric (kWh)	-3063	-1487	-506
Net (kWh) kWh/m^2 (kWh/ft^2)	4802 2 (0.2)	2477 1 (0.1)	26,644 11 (1)
Cost (\$) \$/m^2 (\$/ft^2)	480 0.20 (0.019)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

Results—Annualized Life-Cycle Cost

- Unit costs in \$/m^2 (\$/ft^2)
- Does not include IAQ benefit credit

	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



85% UVGI or additional MERV 12 filtration reduce relative risk by 50%–55%

IAQ Benefit

Operating Scenario	Health Benefit $/m² ($/ft²)	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

Estimated benefit >> annualized cost – but analysis rests on many assumptions and tends not to sway decision making

Photodegradation of Materials

- Affected Materials
- ASHRAE RP-1509

Affected Materials

- UVC can degrade organic materials, for example,
  - Electrical insulation
  - Elastomers and sealants
  - Filter media
  - Gaskets and pipe insulation
  - Furnishings and finishes
- Severity for given exposure varies widely
- More known about UVA and UVB (found in sunlight)
- Basic approach is to use UV-resistant materials whenever possible and shield materials that will degrade significantly
- Can be a problem for retrofits

ASHRAE RP-1509

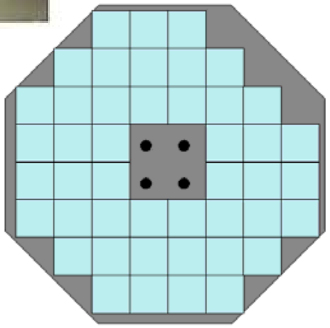
- Investigated 54 materials
- Assumed accelerated tests would be valid
  - Literature review confirmed “reciprocity law”
    - Degradation dependent only on total incident energy
    - Should have similar results if I × t = constant
- Criteria for photodegradation
  - Loss of surface mass—stylus or optical profilometer
  - Physical property changes—thermo-mechanical analyzer (TMA)
  - Composition changes—Fourier transform infrared analyzer (FTIR)
- Developed classification scheme for susceptibility to degradation

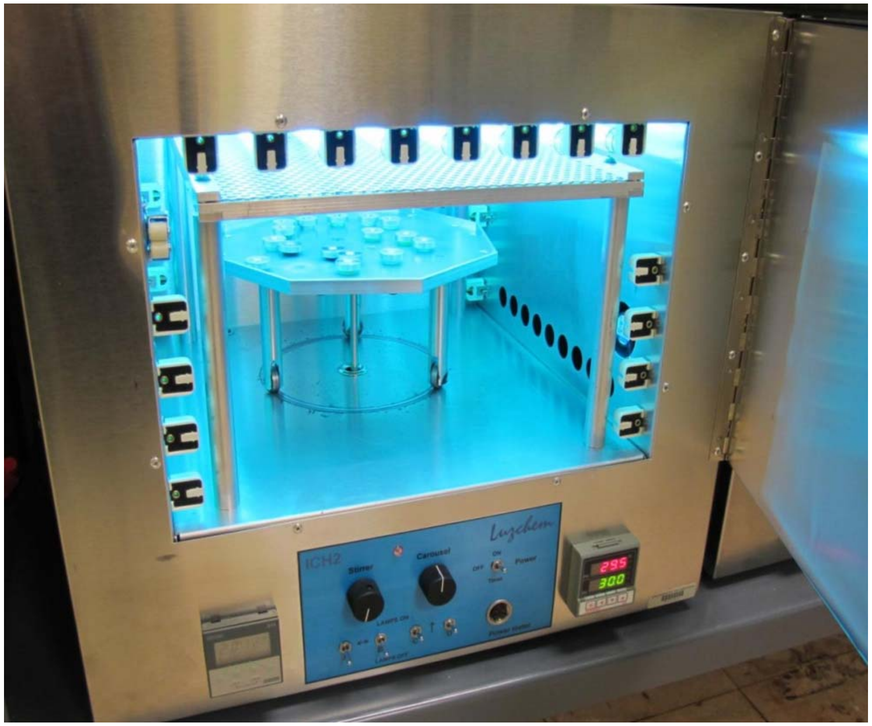
Examples of Materials Tested

- Polished polymers
  - HDPE, aluminum tape
- Elastomers
  - EPDM (ethylene propylene diene monomer) O-ring, silicone O-ring
- Filter media and support materials
  - Cardboard, lofted fiberglass, industrial HEPA
- Miscellaneous materials
  - Elastomeric V-belt, polyurethane door gasket, foam pipe insulation

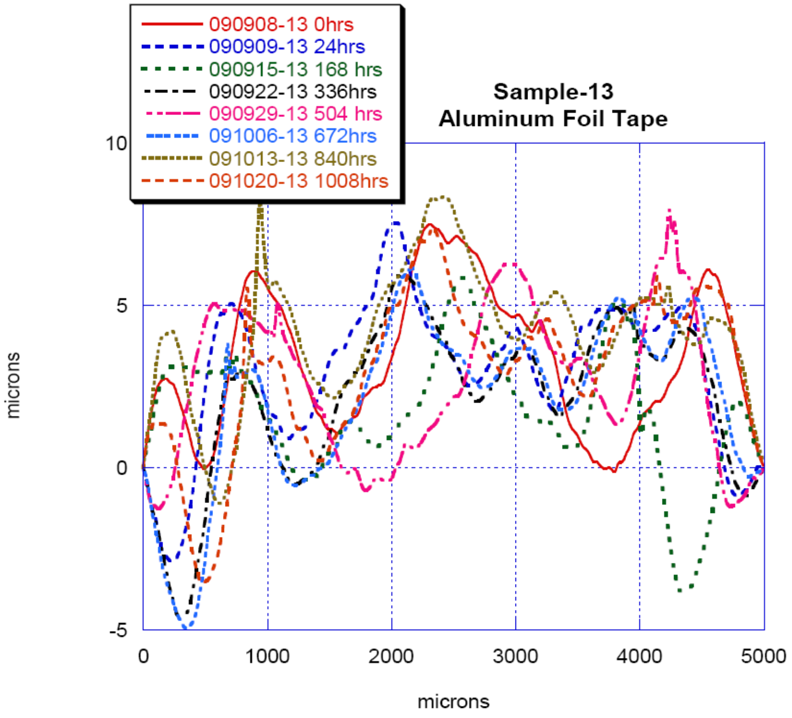
UV Reactor for Accelerated Testing

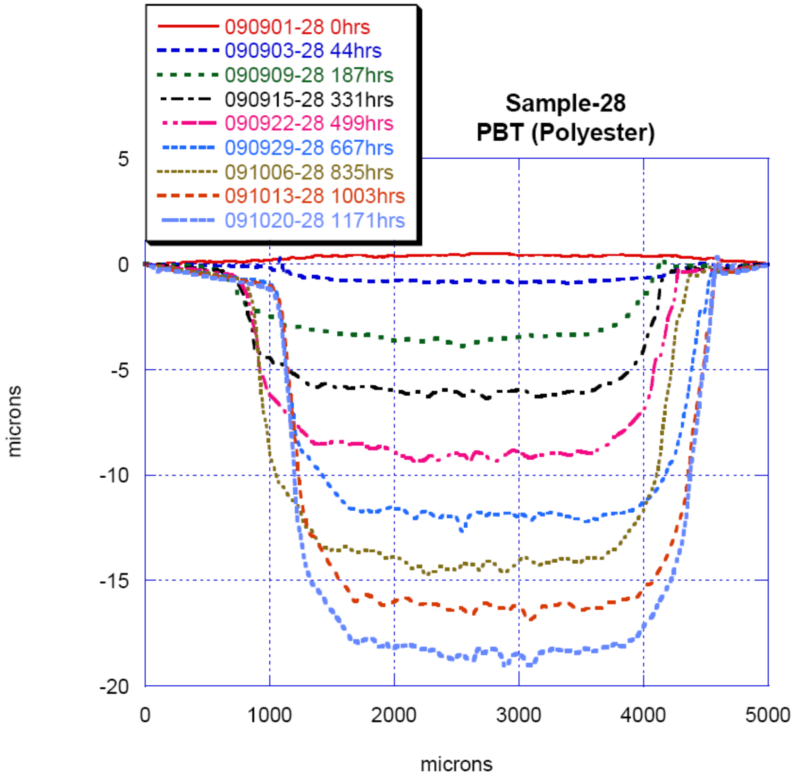
- Samples masked by aluminum, except for 1/8-in. diameter exposed circle





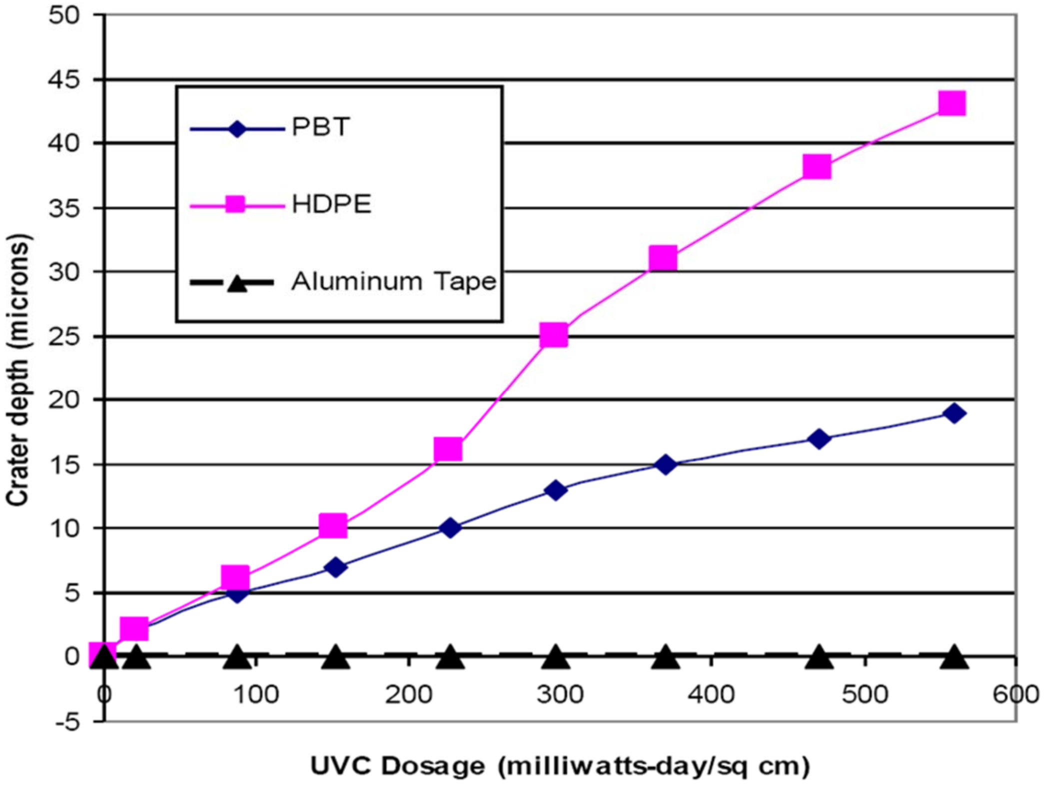
Typical Profilometer Data





Foil tape unaffected, PBT degraded significantly

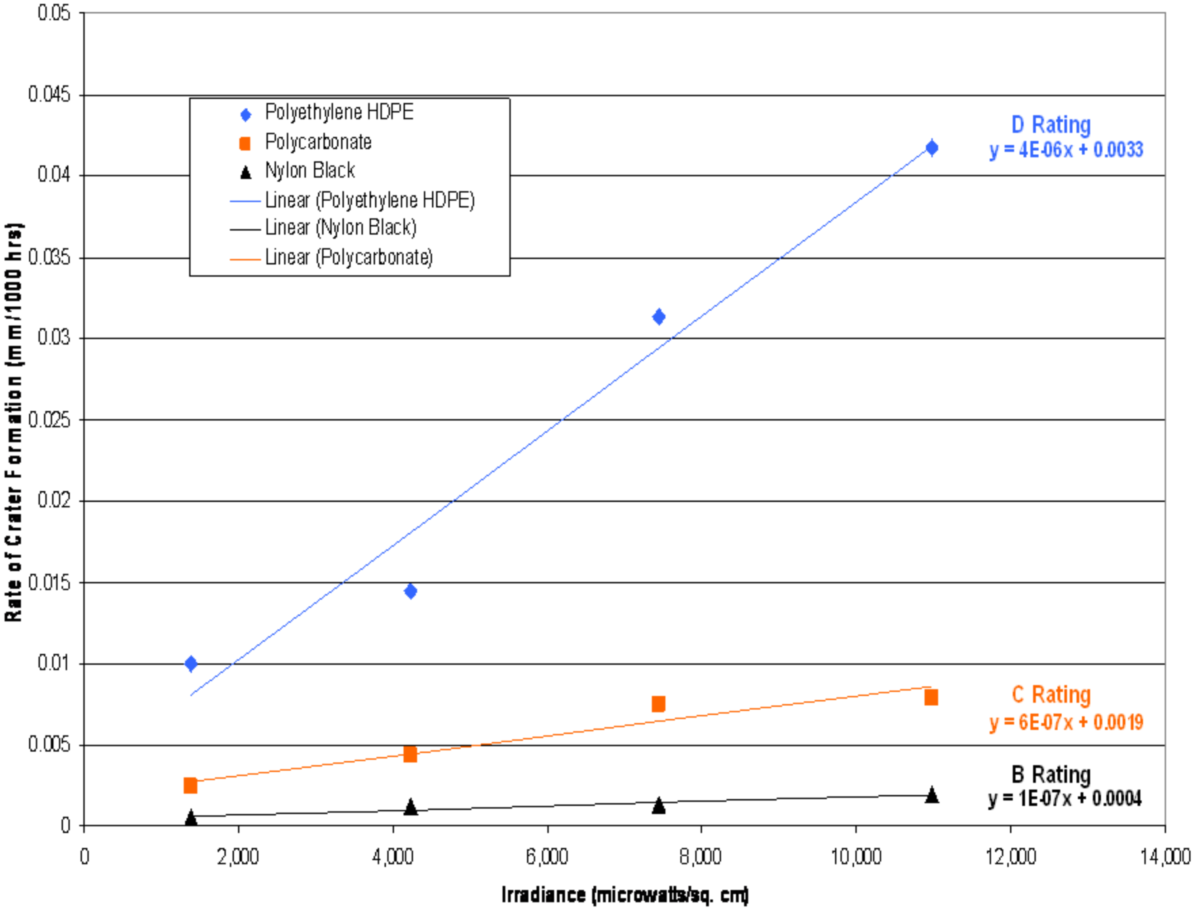
Surface Loss vs. Energy Input



Surface Loss vs. Energy Input

- Test predicts rate of material loss from surface
- Does ***not*** predict time to failure directly
- Failure depends on application, especially thickness of material
- For example, for polybutylene terephthalate (PBT) irradiated for 1200 h with 11,000 μm/cm² 254 nm UVC:
  - 50 μm wire insulation loses 40% of mass
  - 1 cm panel loses ~0.2% of mass

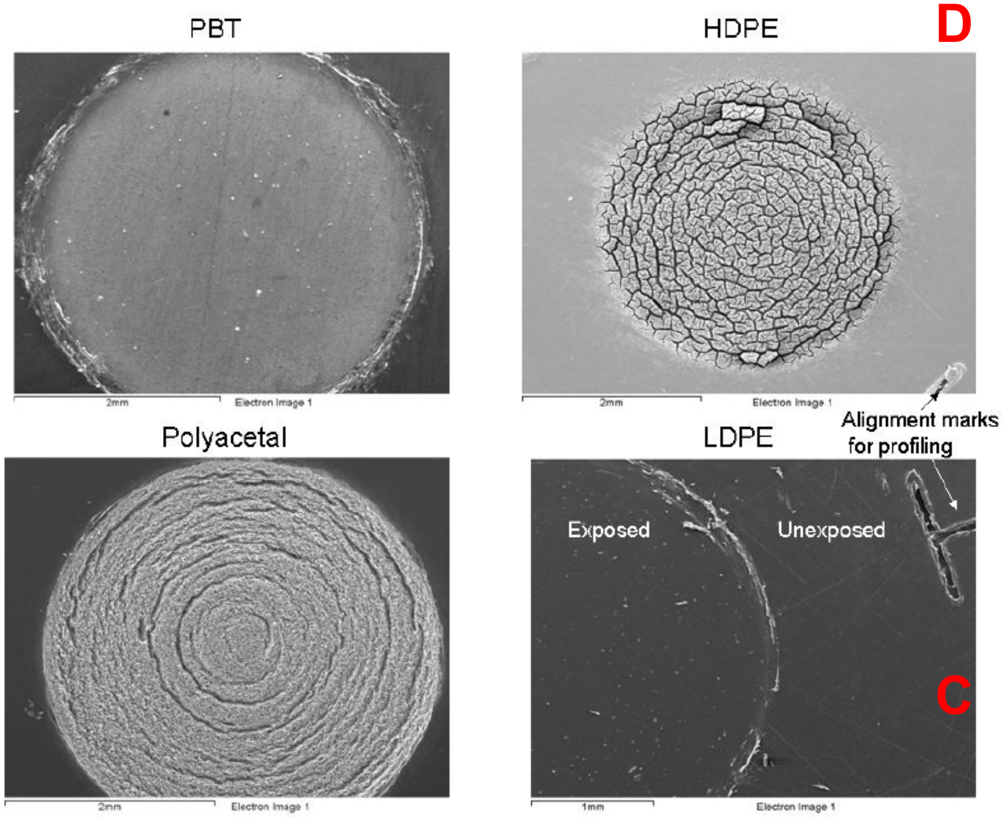
Crater Growth Rate vs. Irradiance



- Linear relationship to irradiance confirms

Classification System—UVC Resistance Rating

- A – No effect
- B – Minor effect (mainly cosmetic changes)
- C – Moderate effect (some cracking/pitting)
- D – Severe effect (structural damage, use not recommended)
- Based on rate of crater growth per unit of UVC energy



UVC Resistance Rating—Polished Polymers

Rating B	Rating C	Rating D
Aluminum tape (*A* Rating)	Polyimide (30)	Acrylic (80)
Formvar (4)	LDPE (30)	PET (90)
Nylon black (10)	ABS (30)	PBT (90)
Natural nylon (10)	Cast epoxy (40)	Polypropylene (200)
Perfluoroethylene (20)	Polyvinyl chloride (40)	HDPE (400)
	Polycarbonate (60)	Polyacetal (700)
	Phenolic resin	

Numbers in parentheses are rate of crater formation per unit of irradiance

UVC Resistance Rating—Elastomers

Rating B	Rating C	Rating D
Copper/petroleum RTV		Acetic Acid RTV
Latex Rubber		
Buna-N O-ring		
EPDM O-ring		
Silicone O-ring		

UVC Resistance Rating—Filter Media and Support Materials

Rating B	Rating C	Rating D
Kimwipe (10)	Printer paper (100)	Polyester* (400)
Hot melt adhesive (70)	Polyurethane strips (100)	Cardboard (1000)
	Industrial HEPA (100–200)	Lofted fiberglass* (7000)
	HEPA consumer (200)	
	Electret (300)	

Numbers in parentheses are rate of crater formation per unit of irradiance

***Structural damage, lost fibers, etc.**

Classification of Miscellaneous Materials

Rating B	Rating C	Rating D
Elastomeric isolator (30)	Polyurethane door gasket (20)	Fiberglass pipe insulation* (90)
Elastomeric V-belt (70)	Mastic duct sealant (400)	Neoprene door gasket* (100)
Fiberglass pipe insulation with foil-backed wrap		Polyethylene foam pipe insulation* (300)
		Styrofoam* (300)

Numbers in parentheses are rate of crater formation per unit of irradiance

***Structural damage, lost fibers, etc.**

RP-1509

- Provides information on effect of UVC on common materials
- Rates resistance according to a somewhat arbitrary classification
- Provides a better basis for selecting materials or making decisions about shielding

UVGI System Maintenance Requirements

- Lamp Replacement
- Lamp and Ballast Disposal
- Visual Inspection
- Radiation Testing

Maintenance —Lamps, Ballasts

- Lamps should be replaced at end of “useful life”
  - Nominal life specified by manufacturer (6000–10,000 h of operation)
  - No less than annually for continuous operation
  - As needed based on measured output
- Lamp disposal
  - Hg is a hazard—recycle lamps properly
  - Learn and follow applicable regulations
- Ballast disposal
  - Old (pre–1979) ballasts contain PCBs—hazardous waste
  - Recycling of all ballasts preferred—reclaim Cu, AL, steel

Maintenance—Visual Inspection

- Use viewing port and/or appropriate protective gear
- Check for
  - Burned out/failing lamps/fixtures (replace)
  - Excessive dust/dirt accumulation (clean—lint free cloth/glass cleaner/isopropyl alcohol—leave no residue)

Maintenance—Measurement

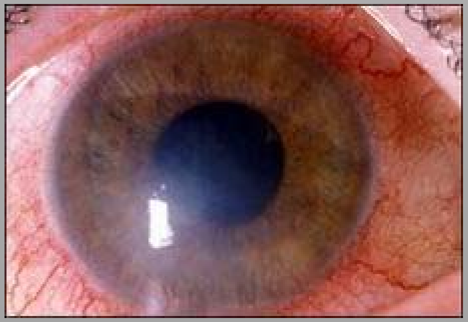
- Radiometer measurements
  - Confirm acceptable output level
  - Confirm acceptable occupied zone exposure for upper-air systems
- In-situ sensors may be considered for fault detection
  - Check relative output level after calibration by high-accuracy instrument
- Highly accurate measurements require costly instrumentation

UV Health and Safety Considerations

- UV Exposure
- Ozone Generation
- Lamp Breakage
- Protective Measures

UV Exposure

- Consequences of UVB and UVC exposure
  - Eye irritation (photokeratitis and conjunctivitis)
    - Blurred vision, blinking, tearing, light sensitivity
    - Develops 4–12 h after exposure
    - Painful but generally reversible
    - Effects may last 48 h
  - Skin irritation (erythema)



UV Exposure

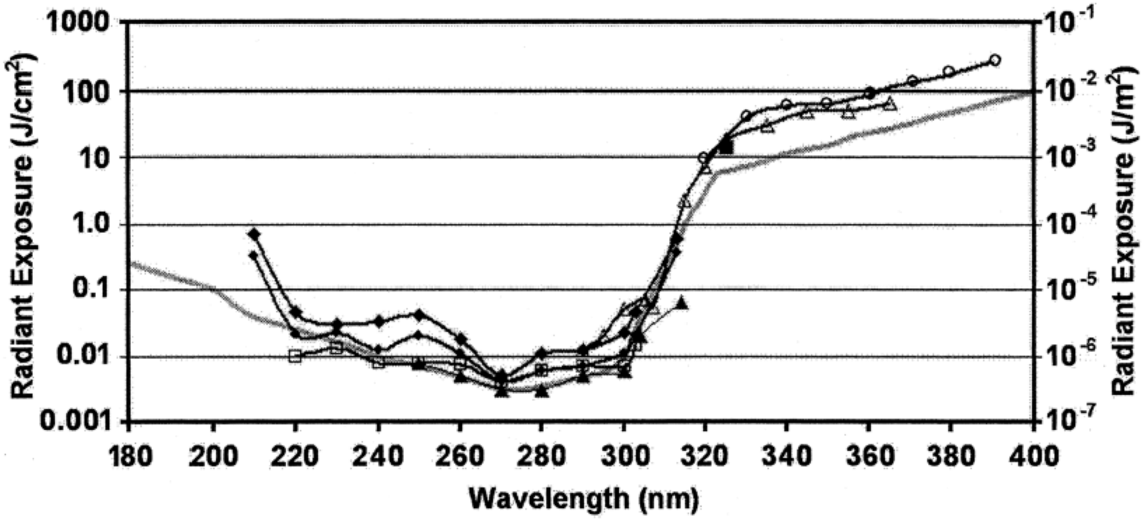


Fig. A2. Ocular action spectra. The ICNIRP UV guideline for exposure is depicted by the shaded, solid line. The data for primate cornea of Pitts and Tredici (1971) are symbolized by a line with a closed circle, ●, of Kurtin and Zuclich (1978) by a line containing an open circle, ○, and of Zuclich and Taboada (1978) by a line containing a closed square, ■. The data for rabbit cornea of Pitts and Tredici (1971) are represented by a line containing a closed diagonal square, ◆, and of Pitts et al. (1977) by a line containing an open triangle, △. The human cornea data of Pitts (1973) are shown by a line with an open square, □, and human conjunctiva data (Cullen and Perera 1994) by a line with a closed triangle, ▲, but the outlier data point at 320 nm apparently resulted from thermal effects or experimental problems, as it is totally inconsistent with environmental experience. Each data point was plotted after adjustment for spectral bandwidth used for each exposure (Sliney and Wolbarsht 1980). A single 193-nm laser threshold point 1 J cm^{-2} is not shown.

Spectral variation of eye irritation

(Source: ICNIRP Guidelines. 2004. *Health Physics* 87(2):171-186.

UV Exposure

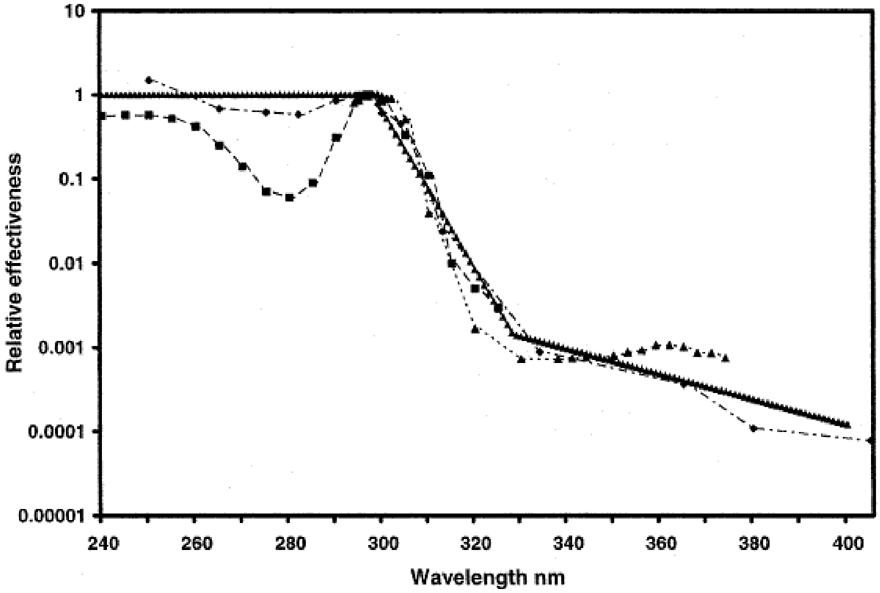


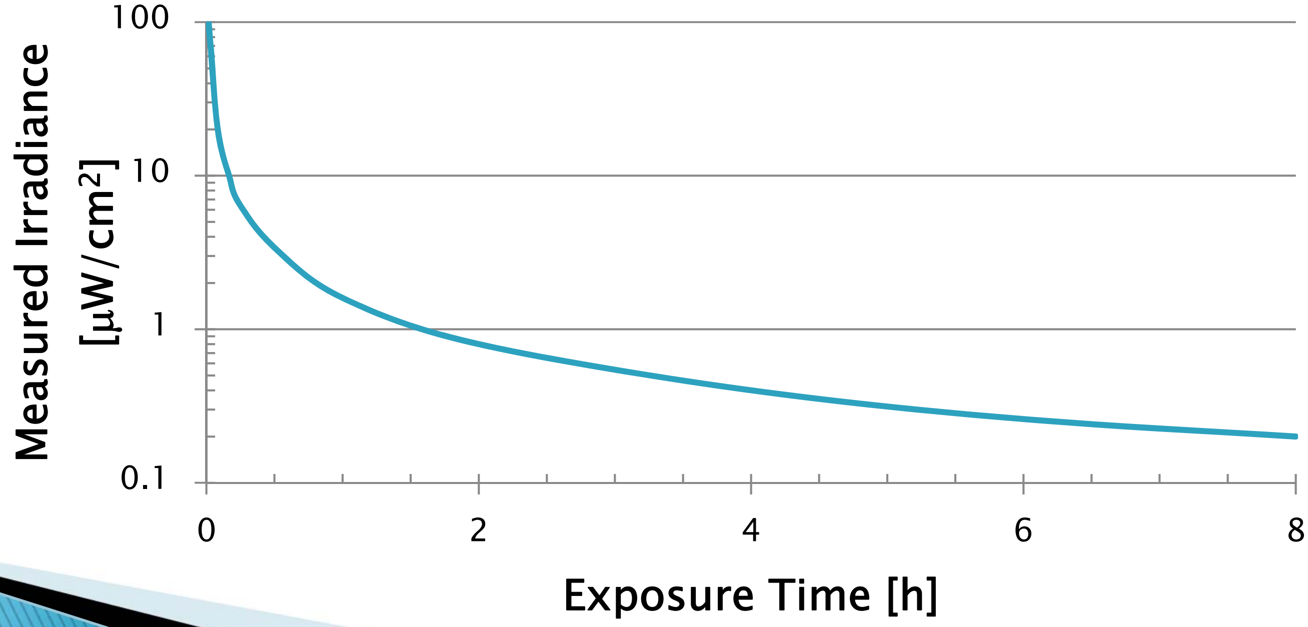
Fig. A1. Erythemal action spectra. The CIE (1998) reference action spectrum for erythema in human skin (solid line), an erythema action spectrum (Anders et al. 1995) determined using dye lasers (triangles), and the CIE (1935) action spectrum (squares) are shown with the action spectrum of human skin adapted from Parrish et al. (1982) for 8 h after irradiation (diamonds). If measured at 24 h, the MED differs below 300 nm.

Spectral variation of skin irritation

(Source: ICNIRP Guidelines. 2004. *Health Physics* 87(2):171-186.)

Exposure Limits

- NIOSH Limits for 253.7 nm UVC
  - 1 s: 600 μW/cm^2
  - 1 min: 100 μW/cm^2
  - 1 hour: 1.7 μW/cm^2
  - 8 hours: 0.2 μW/cm^2 (standard for upper-air)
- In-duct systems may produce 1000-10,000 μW/cm^2
- Safe exposure for in-duct range is ~10 s or less

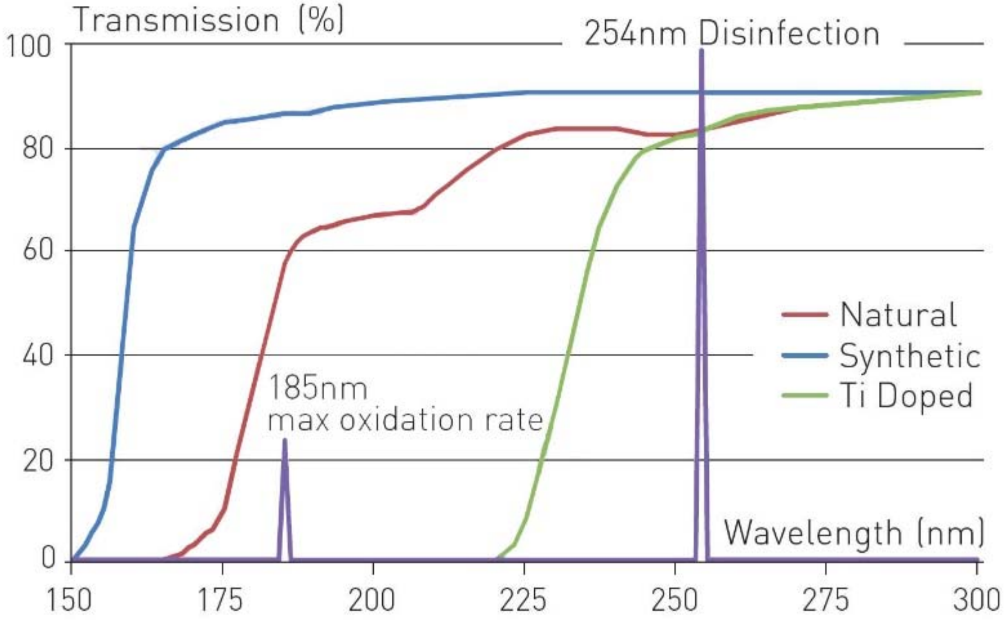


Ozone

- Oxidizing pollutant created by breakup of stable O_2 molecules to form O_3^+
- OSHA PEL/NIOSH REL—0.1 ppmv
- 254 nm UVC does not produce ozone—wavelengths below 240 nm can
- Ozone production of low pressure Hg lamps is small because most radiation is 254 nm—small amount of O_3^+ producing 185

Ozone

- Ozone producing UVC can be filtered by properly selected tube materials or coating
- Periodic testing or continuous monitoring can confirm safe operation



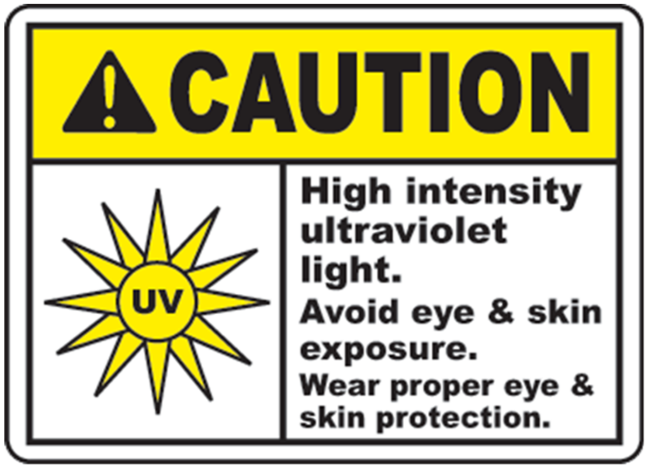
Helios Quartz - http://www.heliosquartz.com

Lamp Breakage

- Lamp breakage releases Hg
- Must be treated as hazardous waste
- Sleeved lamps reduce likelihood of breakage and retain lamp fragments if one does break
- Care must be used in cleanup to remove tube fragments and vacuum up Hg

Protective Measures

- Use full protective clothing when servicing or inspecting operating equipment
- Upper-air
  - Warning signs
  - On/off switches and disconnects
- In-duct
  - Warning labels—doors/access panels
  - Lamp disconnects outside lamp chamber
    - Positive disconnects preferred
    - If switched, locate away from room lighting
  - UV-absorbing view ports



References

- ASHRAE. 2010. Final Report: Study the Degradation of Typical HVAC Materials, Filters and Components Irradiated by UVC Energy (ASHRAE RP-1509).
- ASHRAE. 2019. ASHRAE Handbook—HVAC Applications. Chapter 62,Ultraviolet Air and Surface Treatment. Atlanta: ASHRAE.
- ASHRAE. 2016. ASHRAE Handbook—HVAC Systems and Equipment. Chapter 17, Ultraviolet Lamp Systems. Atlanta: ASHRAE.
- Bahnfleth, W. and J. Firrantello. 2017. Final Report: Field Measurement and Modeling of UVC Cooling Coil Irradiation for HVAC Energy Use Reduction (ASHRAE RP-1738).
- Bahnfleth, W., B. Lee, J. Lau, and J. Freihaut. 2009. Annual Simulation of In-Duct Ultraviolet Germicidal Irradiation System Performance. *Proceedings of Building Simulation 2009*.
- Buaonanno, M, B. Ponnaiya, D. Welch, M. Stanislauskas, G. Randers-Pehrson, L. Smilenov, F. Lowy, D. Owens, and D. Brenner. 2017. Germicidal Efficacy and Mammalian Skin Safety of 222-nm UV Light. *Radiation Research* 187:493-501.

References *(cont.)*

- DeGraw, J., J. T Firrantello, and W. P Bahnfleth. 2012. A Methodology for Assessing Energy Use and Effectiveness of UVGI Systems. *Proceedings of Healthy Buildings 2012*. Brisbane.
- Escombe, A, D. Moore, R. Gilman, M. Navincopa, E. Ticona, B. Mitchell, C. Noakes, C. Martinez, P. Sheen, R. Ramrez, W. Quino, A Gonzalez, J. Friedland, and C. Evans. 2009. Upper-room Ultraviolet Light and Negative Air Ionization to Prevent Tuberculosis Transmission. *PLoS Medicine* 6(3) (March 17).
- Lee, B. and W. Bahnfleth. 2013. Effects of installation location on performance and economics of in-duct ultraviolet germicidal irradiation systems for air disinfection. *Building and Environment*. 67:193-201.
- Knudson, G B. 1986. Photoreactivation of Ultraviolet-irradiated, Plasmid-bearing, and Plasmid-free Strains of Bacillus Anthracis. *Applied and Environmental Microbiology* 52(3) (September): 444-9.
- Kowalski, W. 2009. *Ultraviolet Germicidal Irradiation Handbook: UVGI for Air and Surface Disinfection*. Springer-Verlag Berlin Heidelberg.
- Menzies, D., J. Popa, J. Hanley, T. Rand, and D. Milton. 2003. Effect of Ultraviolet Germicidal Lights Installed in Office Ventilation Systems on Workers’ Health and Wellbeing. *Lancet* 362 (9398) (November 29):1785-91.

References (cont.)

- NIOSH. 2009. Environmental Control for Tuberculosis: Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for Healthcare Settings. http://www.cdc.gov/niosh/docs/2009-105/pdfs/2009-105.pdf.
- Wells, W.F. 1943. Air Disinfection in Day Schools. *American Journal of Public Health and the Nation's Health* 33(12) (December):1436-43.
- Wells, W.F. 1945. Circulation in Sanitary Ventilation by Bactericidal Irradiation of Air. *Journal of the Franklin Institute* 240(5):379-95.
- Wong, T., T. Woznow, M. Petrie, E. Murzello, A. Muniak, A. Kadora, and E. Bryce. 2016. Postdischarge decontamination of MRESA, VRE, and Clostridium difficile isolation rooms using 2 commercially available automated ultraviolet-C-emitting devices. *American Journal of Infection Control* 44:416-420
- Yi, Wang, C. Sekhar, W. Bahnfleth, D. Cheong, J. Firrantello. 2016. Effects of Ultraviolet Coil Irradiation Systems on Air-side Heat Transfer Coefficient and Low △T Syndrome in a Hot and Humid Climate. *STBE* (formerly *Science and Technology for the Built Environment*) 23:582-593.
- Yi, W., C. Sekhar, W. Bahnfleth, K. W. Cheong, J. Firrantello. 2016. Effectiveness of an ultraviolet germicidal irradiation system in enhancing cooling coil energy performance in a hot and humid climate. *Energy and Buildings* 130:321-29.

Questions?

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