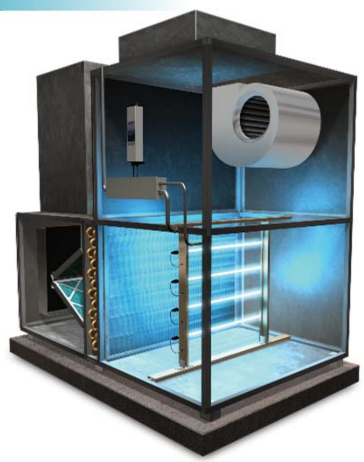
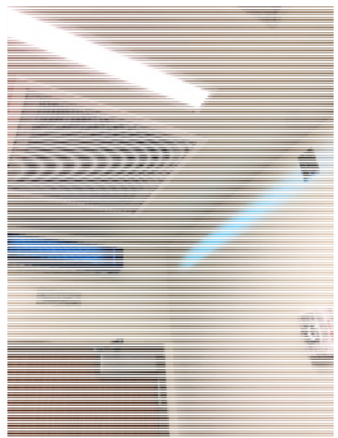
Reducing Infectious Disease Transmission with UVGI





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Learning Objectives

- Describe how germicidal ultraviolet light inactivates microorganisms
- Compare the ultraviolet susceptibility of different pathogens in terms of the UV rate constant
- Use dose-response relationships in the design of UVGI systems
- Understand germicidal light source options and their most important application characteristics.
- Distinguish between and the main types ultraviolet air and surface treatment equipment and their applications

Introduction

Most Deadly Diseases – Airborne and Fomite transmission

(World Health Report, WHO 2013)

Disease	Annual Mortality (1995 data)
Acute lower respiratory infections	4.4 million
Diarrheal diseases	3.1 million
Tuberculosis	3.1 million
Measles	>1 million
Pertussis	355,000

Transmission commonly occurs indoors due to proximity and favorable environment for pathogens

Factors Affecting Airborne Disease Transmission – Wells-Riley Equation

$$C = S\left[1 - \exp\left(-Iqpt / Q\right)\right]$$

- C = new infections
- S = number of susceptibles
- I = number of infectors
- q = number of infectious doses
- p = pulmonary ventilation rate per susceptible
- t = exposure time
- Q = flow rate of uncontaminated air

- Ventilation reduces risk by reducing exposure
- Filters and air disinfection device performance can be expressed as equivalent ventilation rate

Disinfection using UV light has a long history

- 1892 Germicidal effect of UV on B. anthracis shown
- 1909 First UV water treatment plant
- 1936 Overhead systems applied in hospitals
- 1937 Upper air systems applied in schools
- 1940 Application to HVAC systems
- 1999 WHO recommends UV for TB control
- 2003 CDC sanctions use of UV for TB control

Reported Effectiveness Air Disinfection

- Wells, Wells, and Wilder (1942)
- Interventions in two schools in 1937
- Upper air UVGI
- Tracking of infectious disease outbreaks

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 experimental 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.*

[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.

Am. J. Hygiene (1942)

Reported Effectiveness Air Disinfection

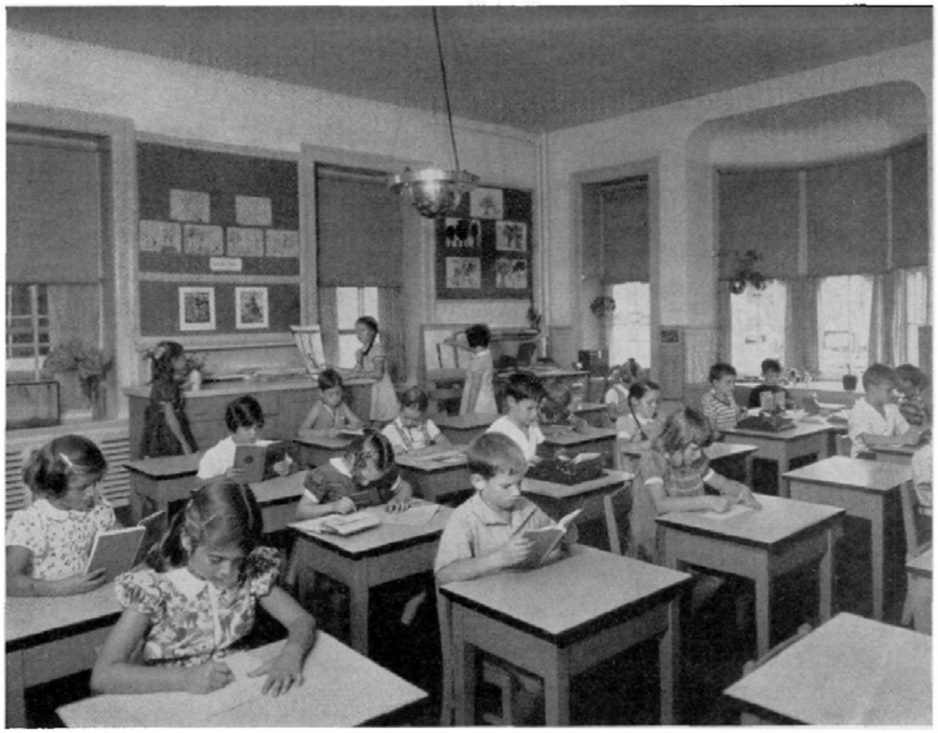
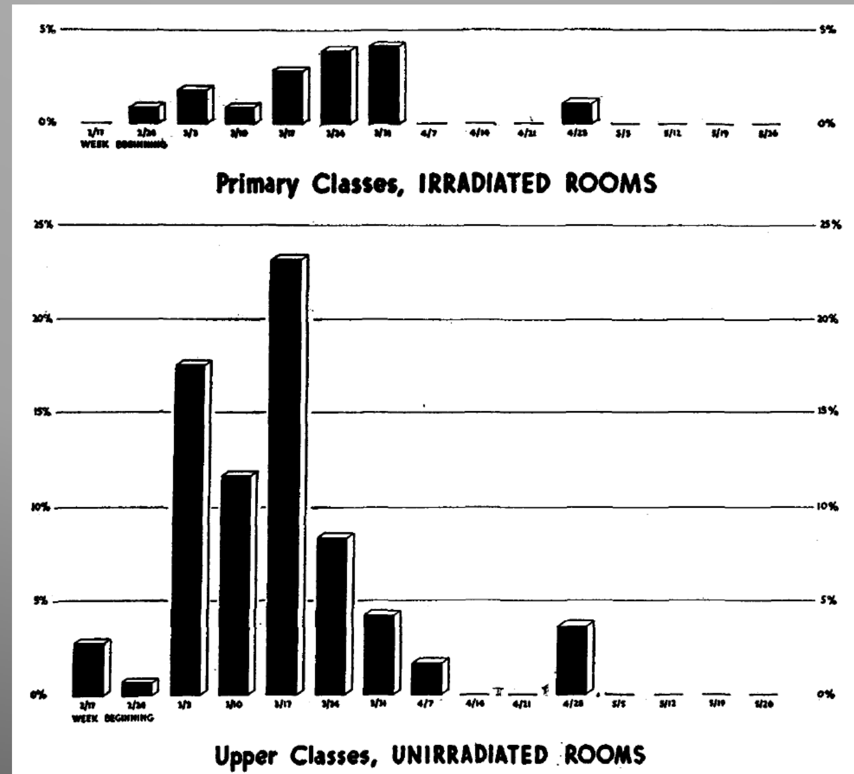


FIGURE 1. Classroom, Germantown Friends School, central radiant sources.



Reported Effectiveness Room Disinfection

- Compare 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

American Journal of Infection Control 44 (2016) 416-20

Contents lists available at ScienceDirect

American Journal of Infection Control

journal homepage: www.ajicjournal.org

Major article

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

Titus Wong MD, MHSc, FRCPC [a,b,1], Tracey Woznow BSc, BEd(Sec) [a], Mike Petrie [c], Elena Murzello BScN, MBA [d], Allison Muniak MASc [d], Amin Kadora MBA [e], Elizabeth Bryce MD, FRCPC [a,b,*,1]

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[b] Department of Pathology and Laboratory Medicine, Faculty of Medicine, University of British Columbia, Vancouver, BC, Canada
[c] Business Initiatives and Support Services, Lower Mainland Health Authorities, Vancouver, BC, Canada
[d] Quality and Patient Safety, Vancouver Coastal Health, Vancouver, BC, Canada
[e] School of Business, Capilano University, North Vancouver, BC, Canada

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.

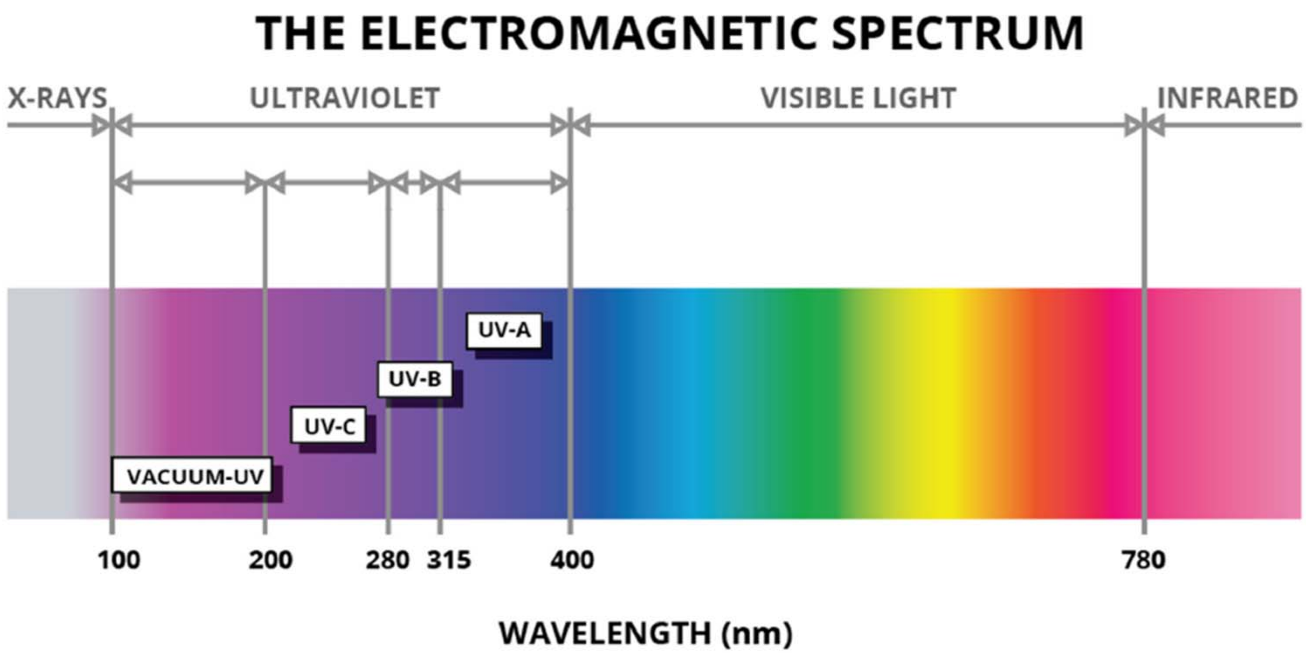
Outline

- UVGI Disinfection
- Inactivation Rate Constants
- Germicidal Sources
- UVGI Systems and Applications
- Photodegradation of Materials
- Maintenance
- Health and Safety Considerations

UVGI Fundamentals

- UV Spectrum
- Microbial Dose Response
- Microbial Susceptibility

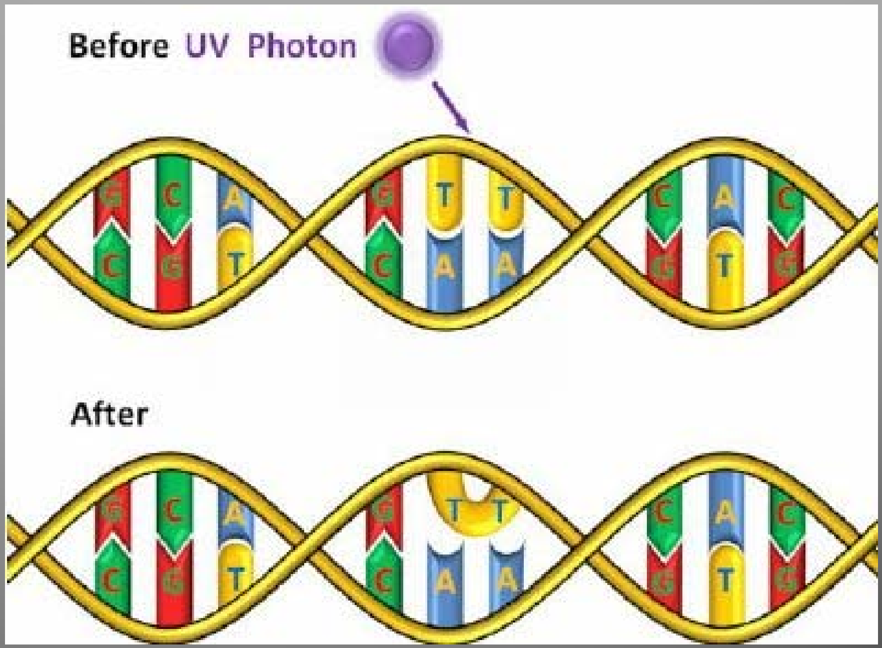
Optical Radiation (1 nm – 1mm)



State of the art is based on 254 nm UVC
“Ultraviolet Germicidal Irradiation” (UVGI)

Germicidal Action of UVC

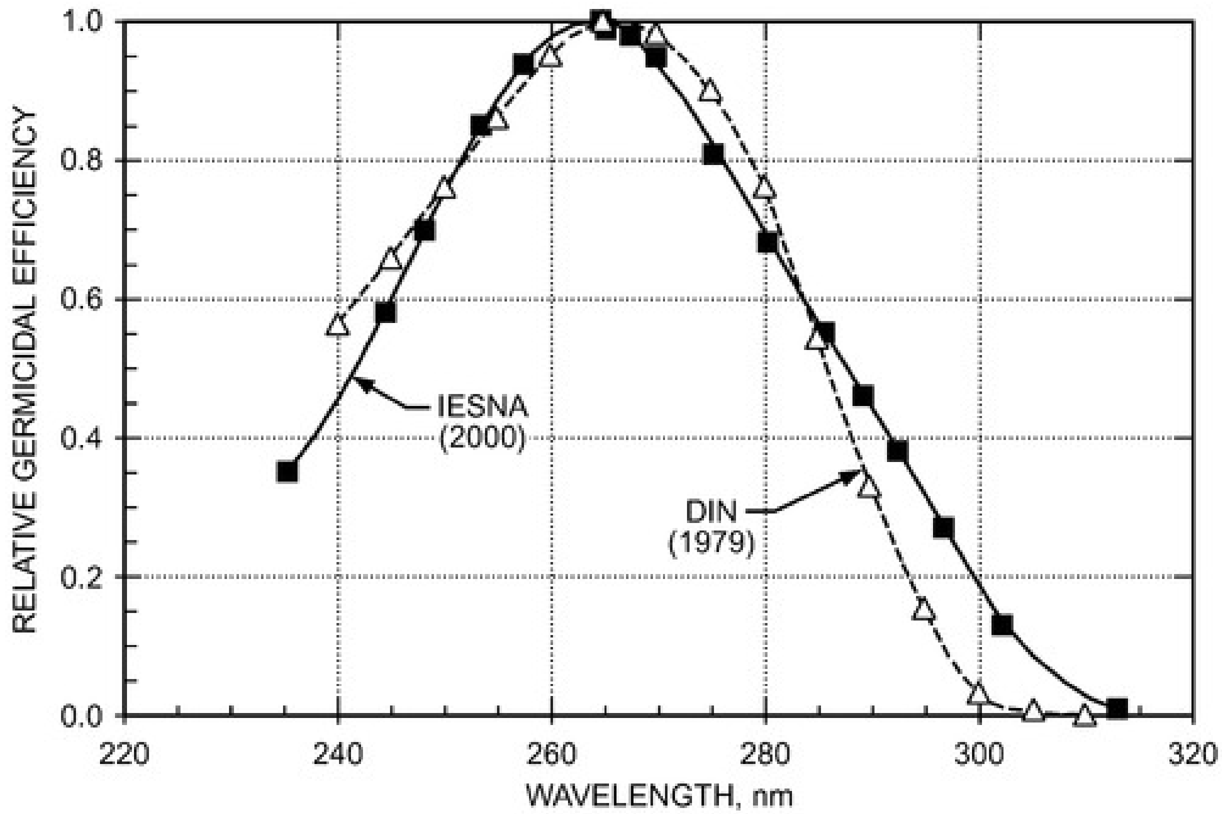
- UVC damages DNA/RNA of microorganisms (virus, bacteria, fungi)
- Microorganisms *inactivated*, i.e., become unable to replicate



Martin Hesseling, Hochschule Ulm

Germicidal Action Spectrum

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



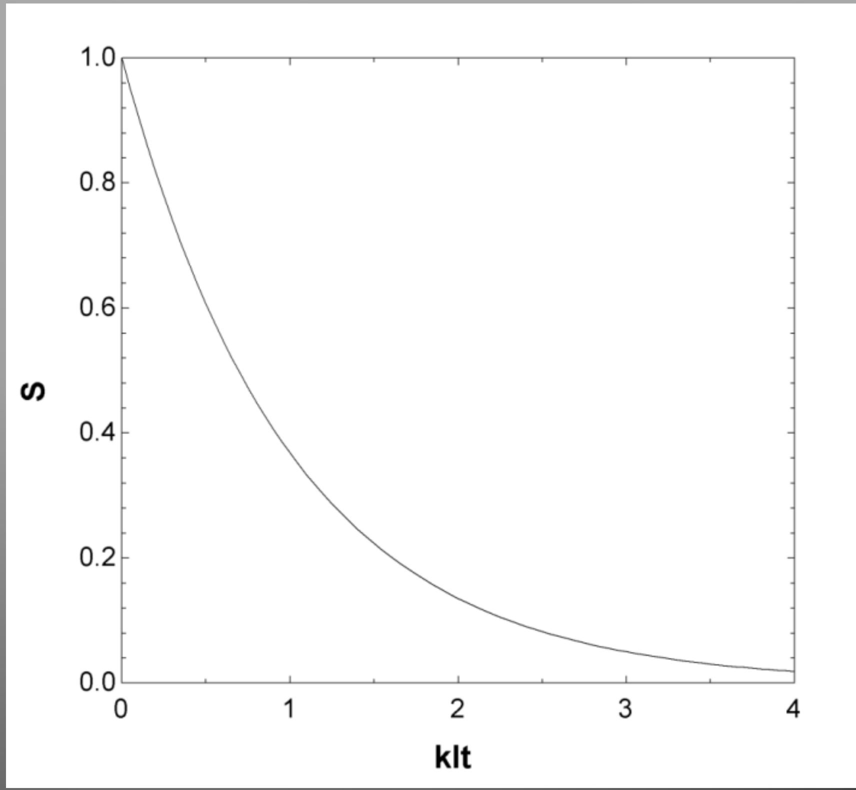
2019 *ASHRAE Handbook—HVAC Applications*, Ch. 60, Fig. 3

Microbial Dose Response to UVGI

- To a first approximation:

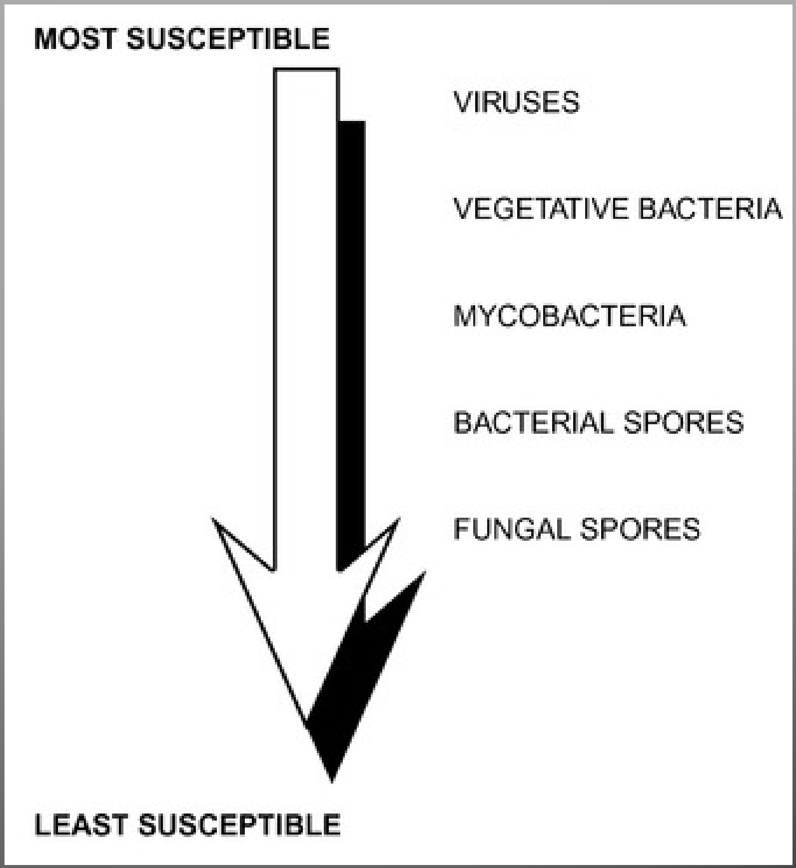
$$S = \exp(-kIt)$$
$$= \exp(-kD)$$

  - S = surviving fraction of initial population
  - k = deactivation rate constant (cm^2/μW–s)
  - I = UV fluence (μW/cm^2)
  - t = duration of exposure (s)
  - It = D = “dose” (μJ/cm^2)



Microbial Response to UVGI – *k*

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

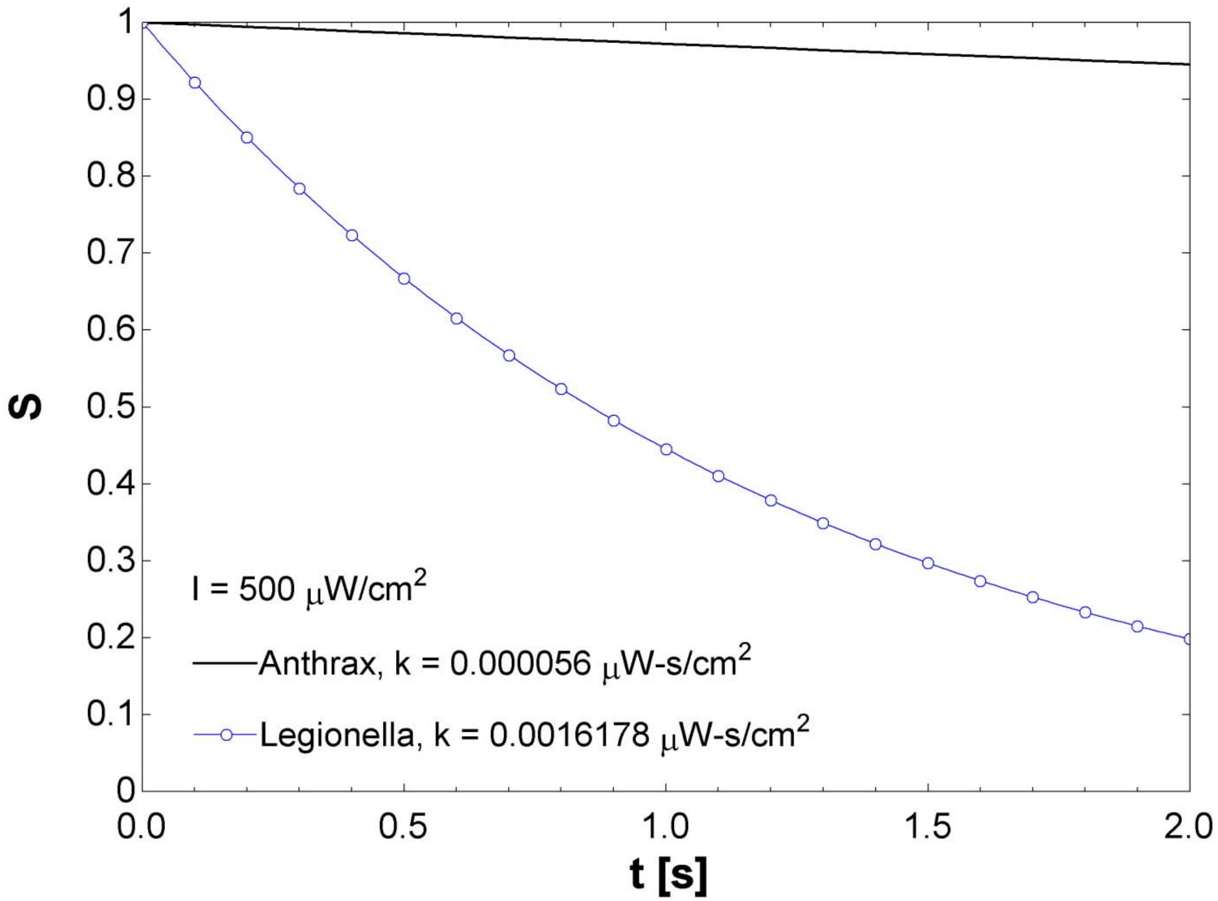


Representative Values ($cm^2/\mu W\text{-}s$)

- Bacillus anthracis (bacterial spore)
  - Water: 0.000056
  - Surface: 0.0002702
- Mycobacterium tuberculosis (vegetative bacteria)
  - Water: 0.0004773
  - Air: 0.0047210
- Influenza A (RNA virus)
  - 0.0010103 (water)
  - 0.0011900 (air)
- Measles: 0.0010510 (RNA virus, water)
- MHV coronavirus: 0.00377 (RNA virus, air)

Sources: Kowalski, Wladyslaw. 2009. *Ultraviolet Germicidal Irradiation Handbook.* Berlin: Springer-Verlag Berlin Heidelberg.
. Walker, C. and G. Ko. 2007. Environ. Sci. Technol. 41:5460-5465. (Coronavirus)

Effect of *k* on Survival

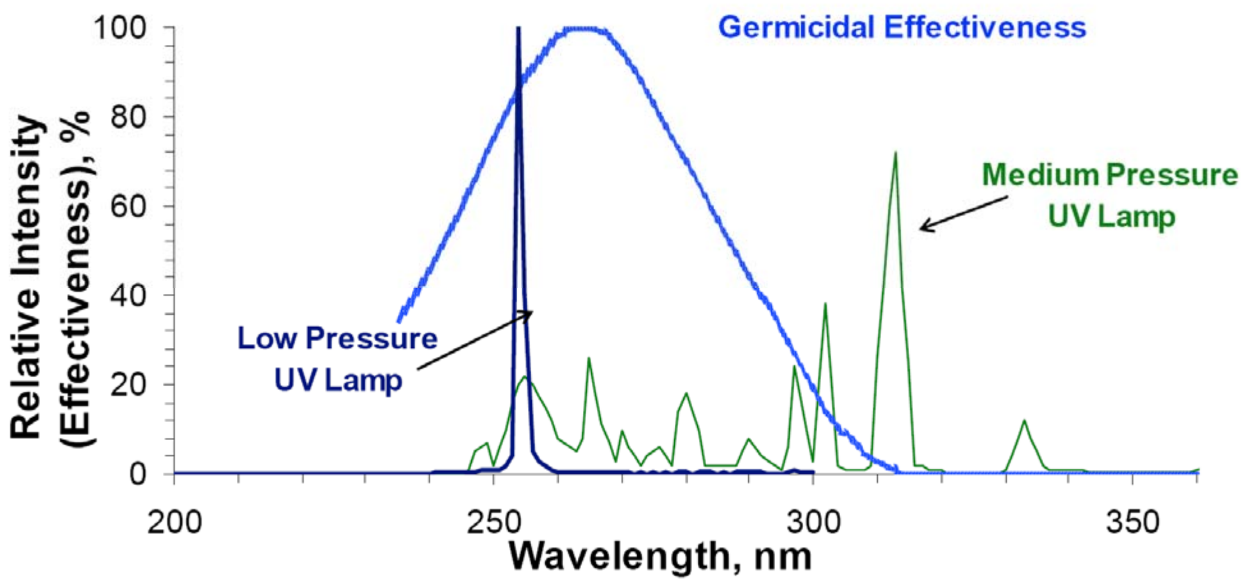


UVGI Equipment

- Lamps
- Ballasts
- Impact of Ballast Selection
- Operating Characteristics
- Effects of Important Environmental Factors

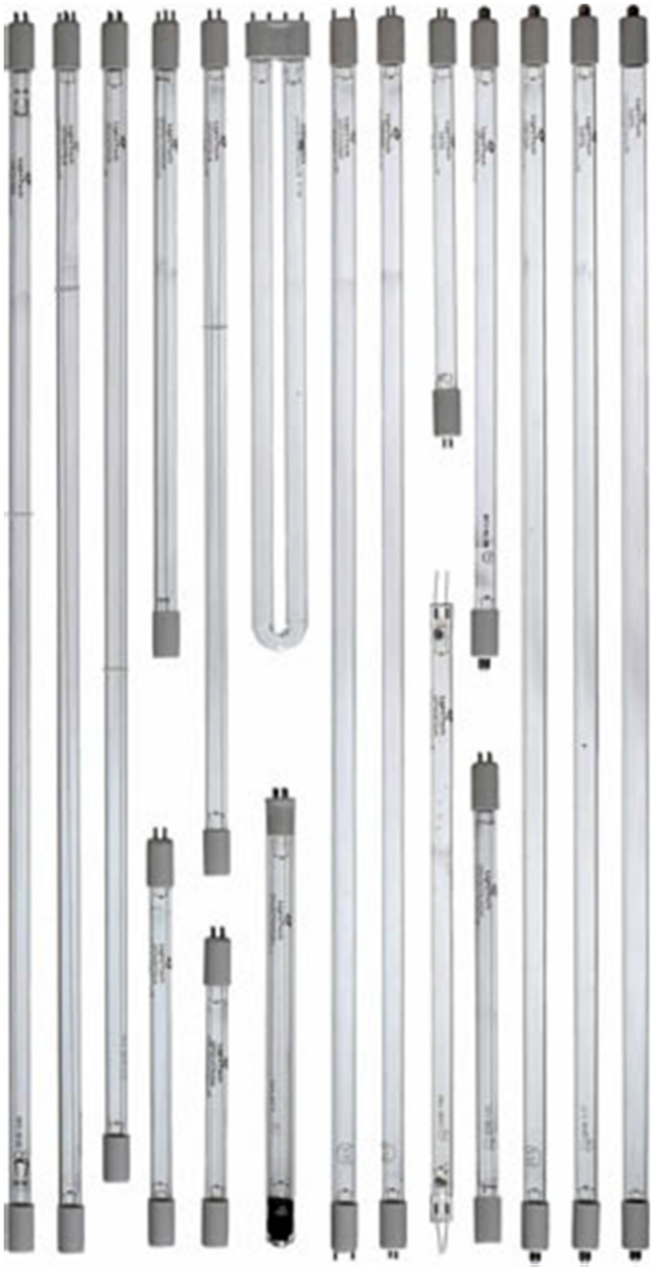
Lamps

- 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



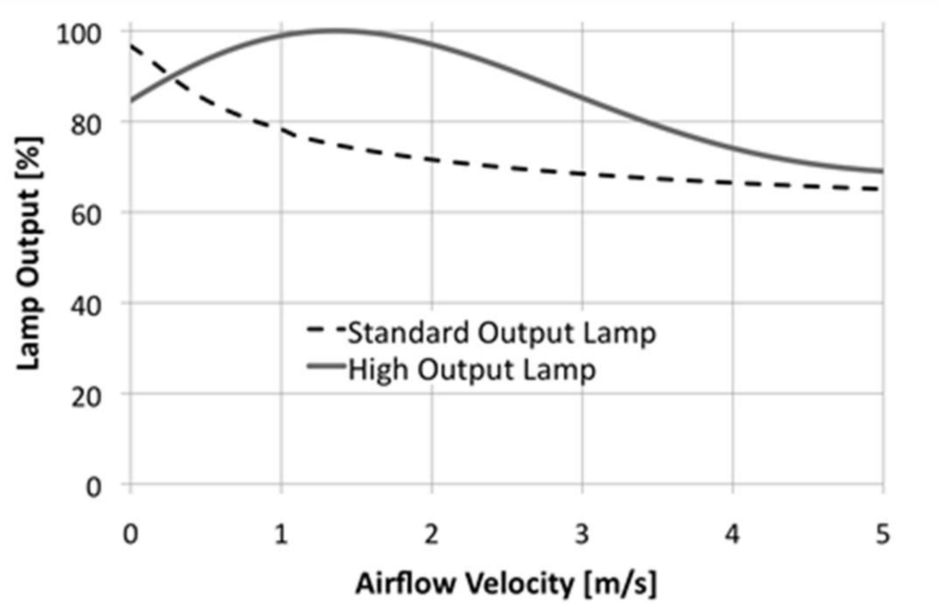
Lamps

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



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

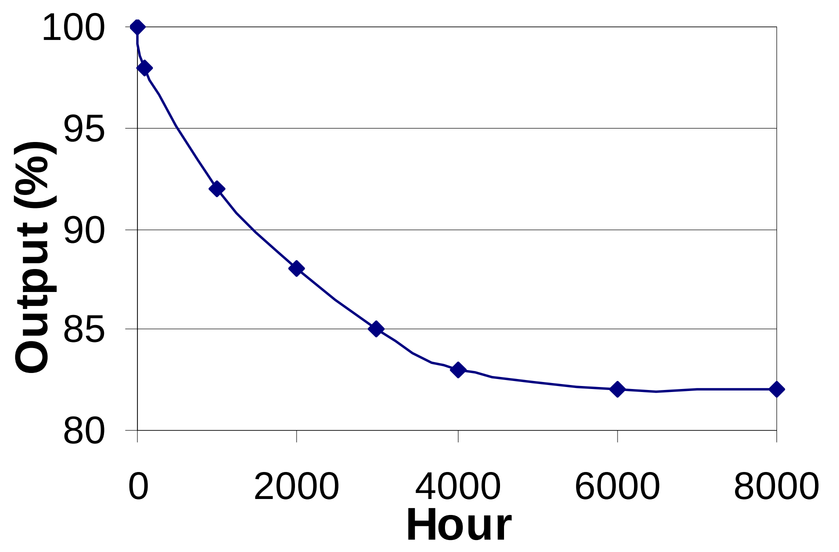
- Starting mode
  - Preheat
  - Rapid start
  - Instant start
- Types
  - Magnetic
  - Electronic
- Dimming ballasts are available but not in common use

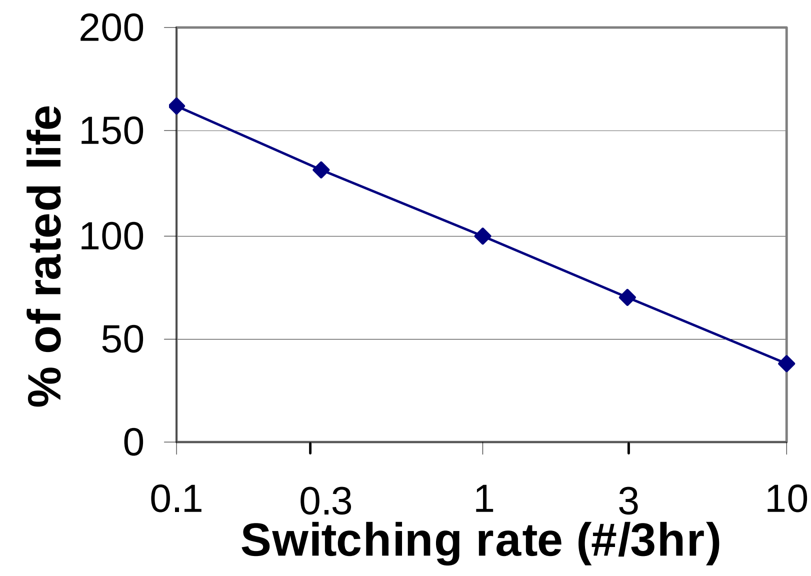
Impact of Ballast Selection on Lamp Performance

- 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





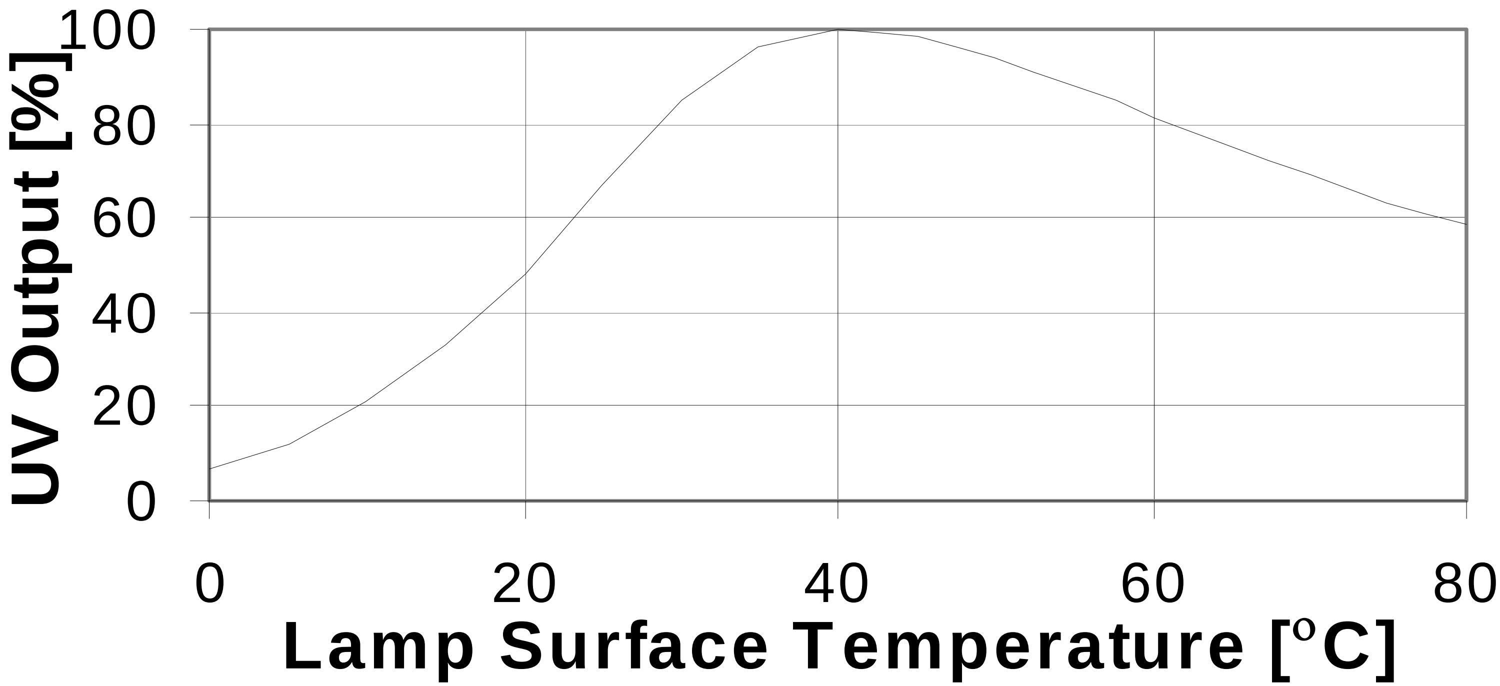
Depreciation

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

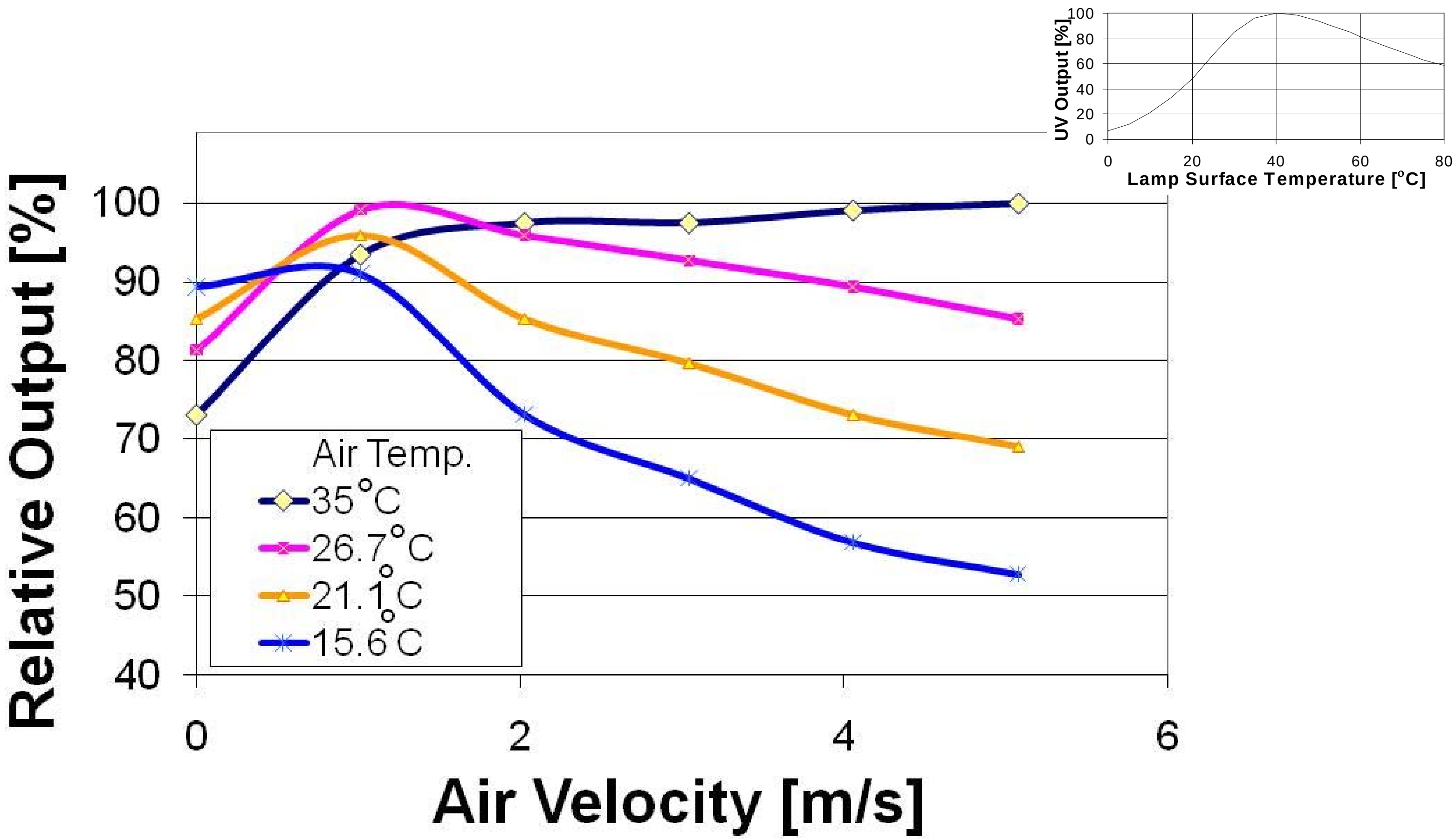
Typical Wind Chill Curve



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

Effect of Air Temperature and Speed

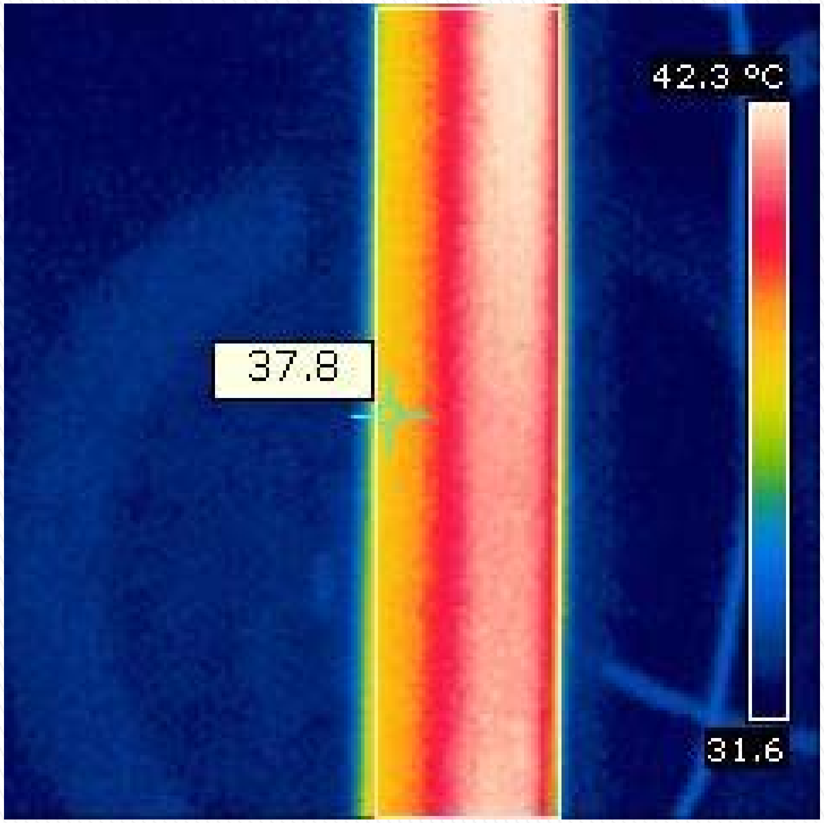
(Standard output lamp, cross flow)



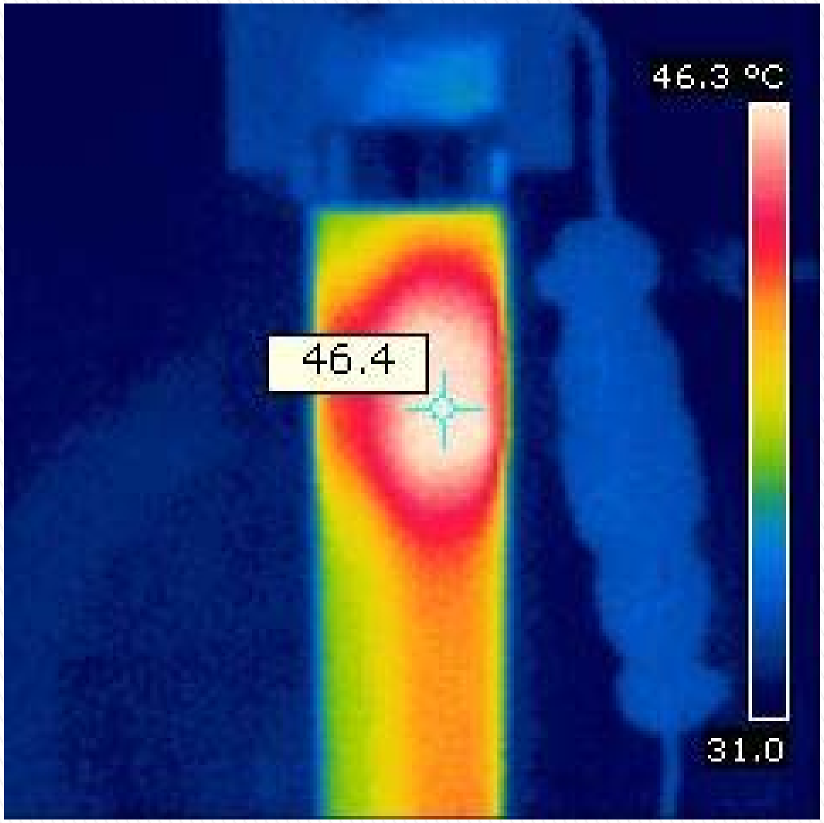
1 m/s = 196 ft/min, 15.6°C = 60°F, 35°C = 95°F

Temperature of Lamp in Cross Flow

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

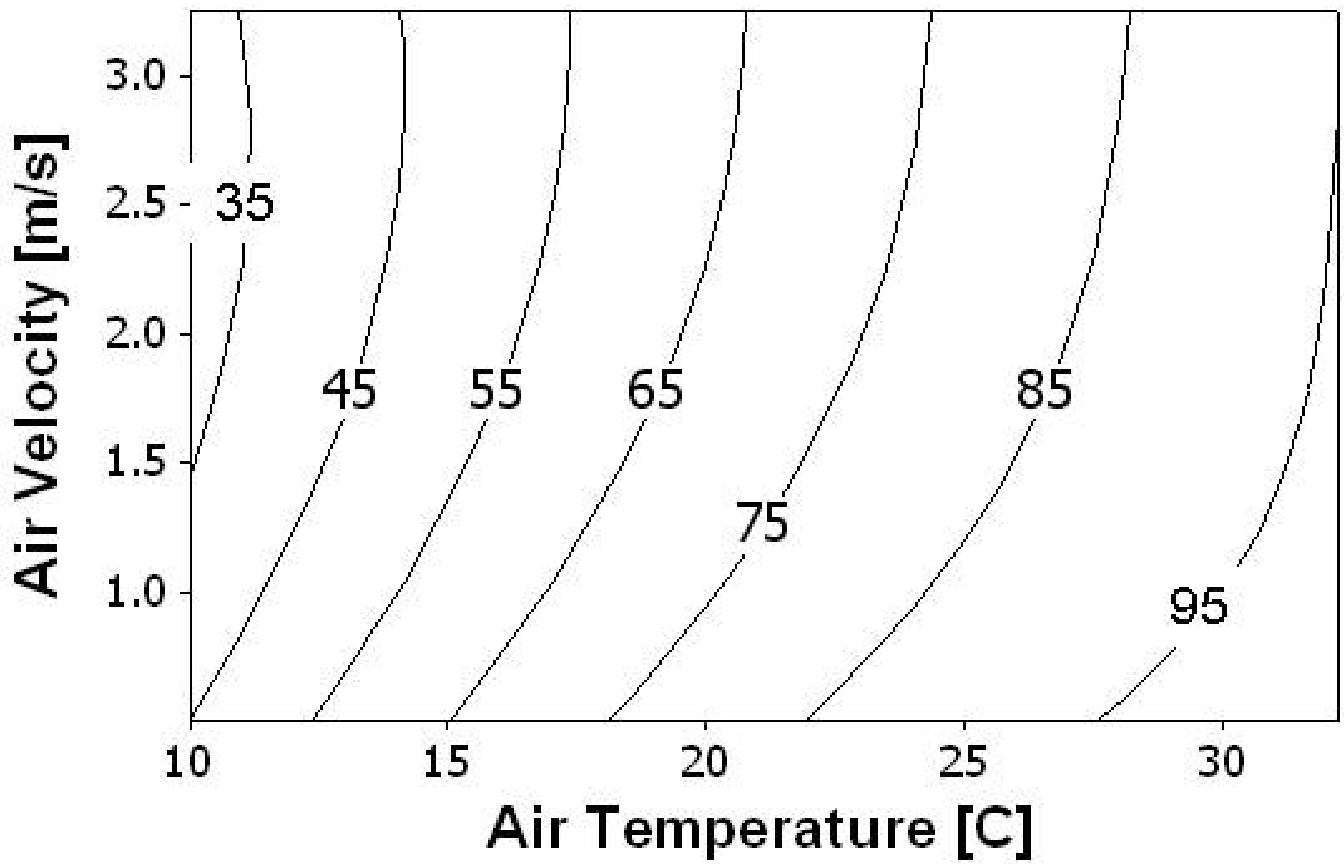


Center (flow left to right)



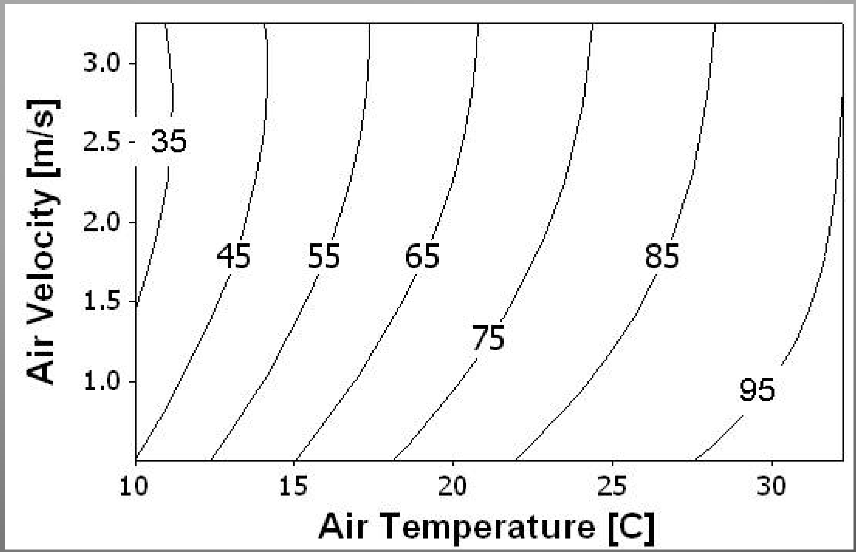
Socket end
(hot spot at cathode)

Lamp Wind Chill Map



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

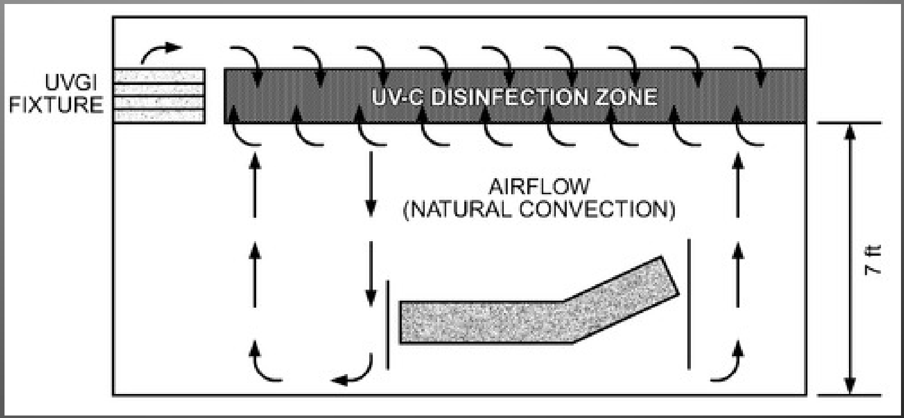


UVGI Applications and System Design Principles

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

Upper Room Disinfection

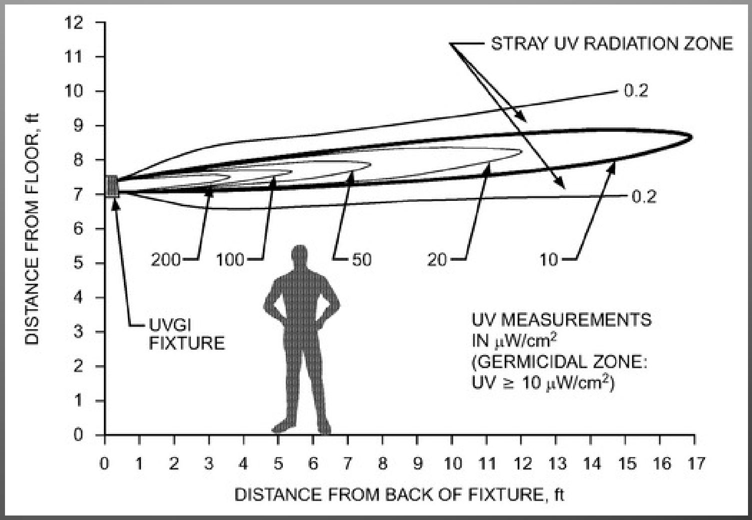
- Fixtures located above occupied zone
- Fixture directs UVC horizontally to create a disinfection zone
- Natural or forced air movement brings contaminated air into zone



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

Upper Room 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

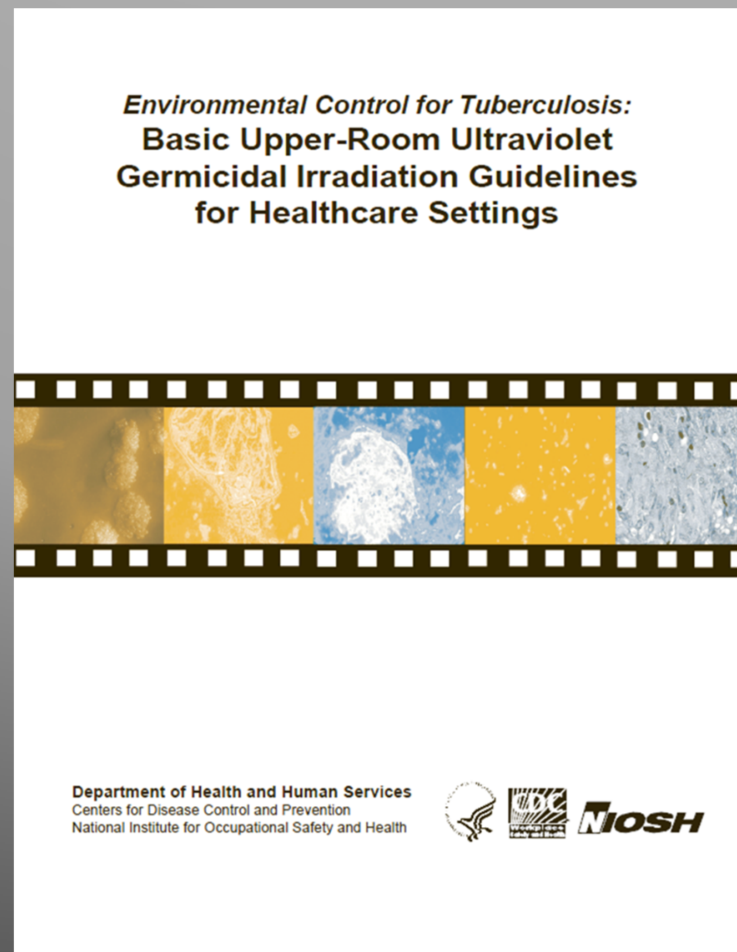
Upper Room Disinfection

- Oldest type of air disinfection system
- Good application for standard lamps
- Approved by U.S. Centers for Disease Control and Prevention/ 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 Room Design Guidelines

- Irradiance
  - Arrange lamps for uniform irradiance
  - 30 μW/cm^2 to 50 μW/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

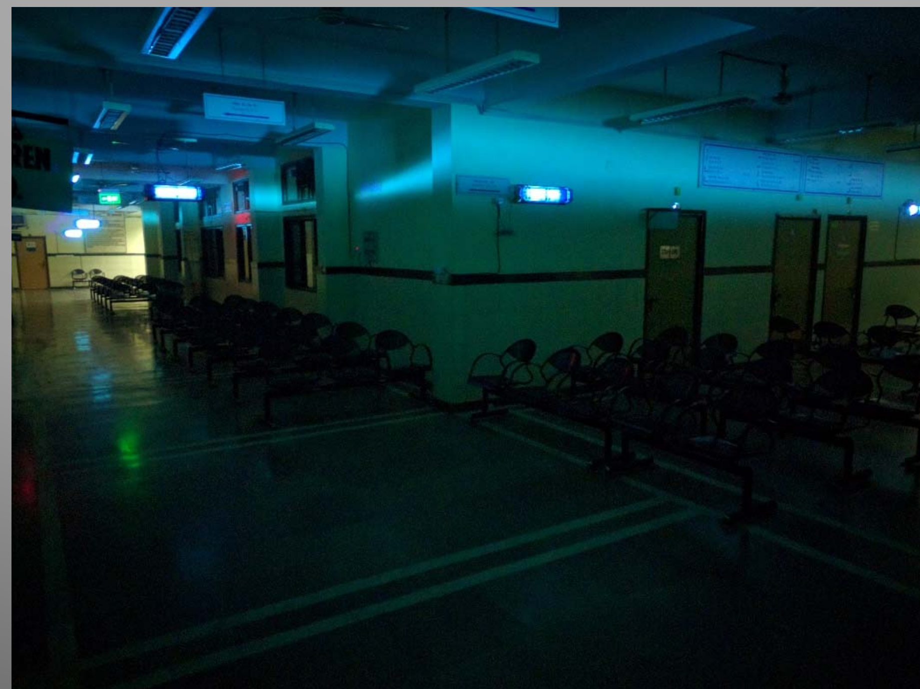


Environmental Control for Tuberculosis:
Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for Healthcare Settings

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

NIOSH (2009) Upper Room Design Guidelines

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

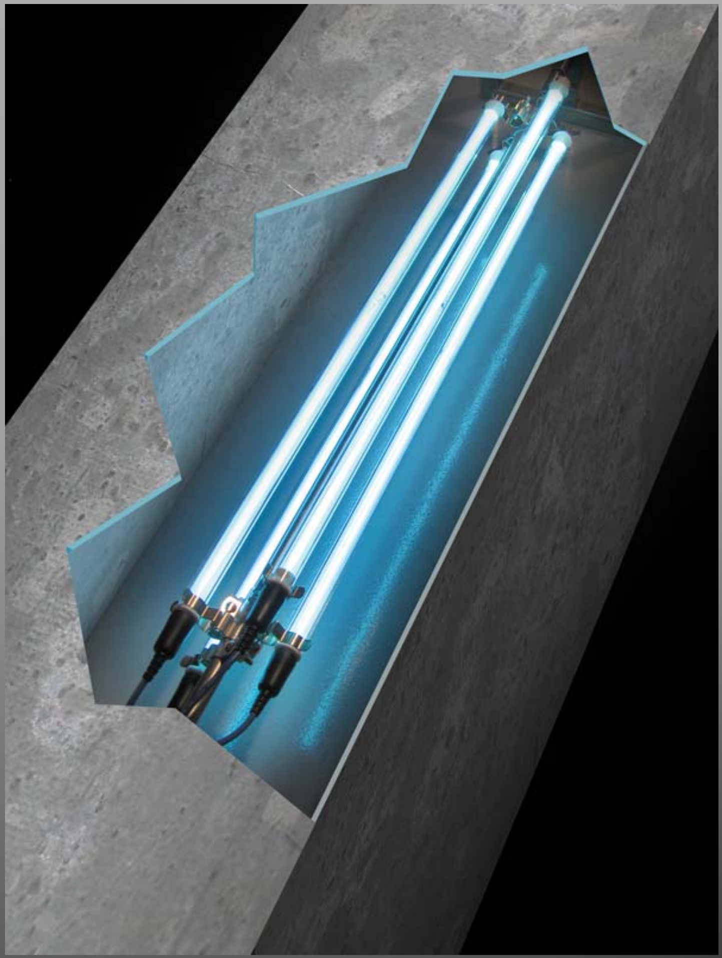


Portable UVGI Unit

- Lamps in enclosure
- Fan – 450 /1000 cfm (212 / 472 L/s)
- HEPA or ULPA filtration can be added

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
- Typical target is 85% single pass inactivation at design value of k but may be much higher
- "Typical" system ~0.02 W/cfm (0.04 W/(L/s))



Air-Handler "In-Duct" Installation

Downstream coil surface/air installation

Air-Handler "In-Duct" Installation

- System designed for 99.98% single-pass inactivation

In-Duct Air Disinfection

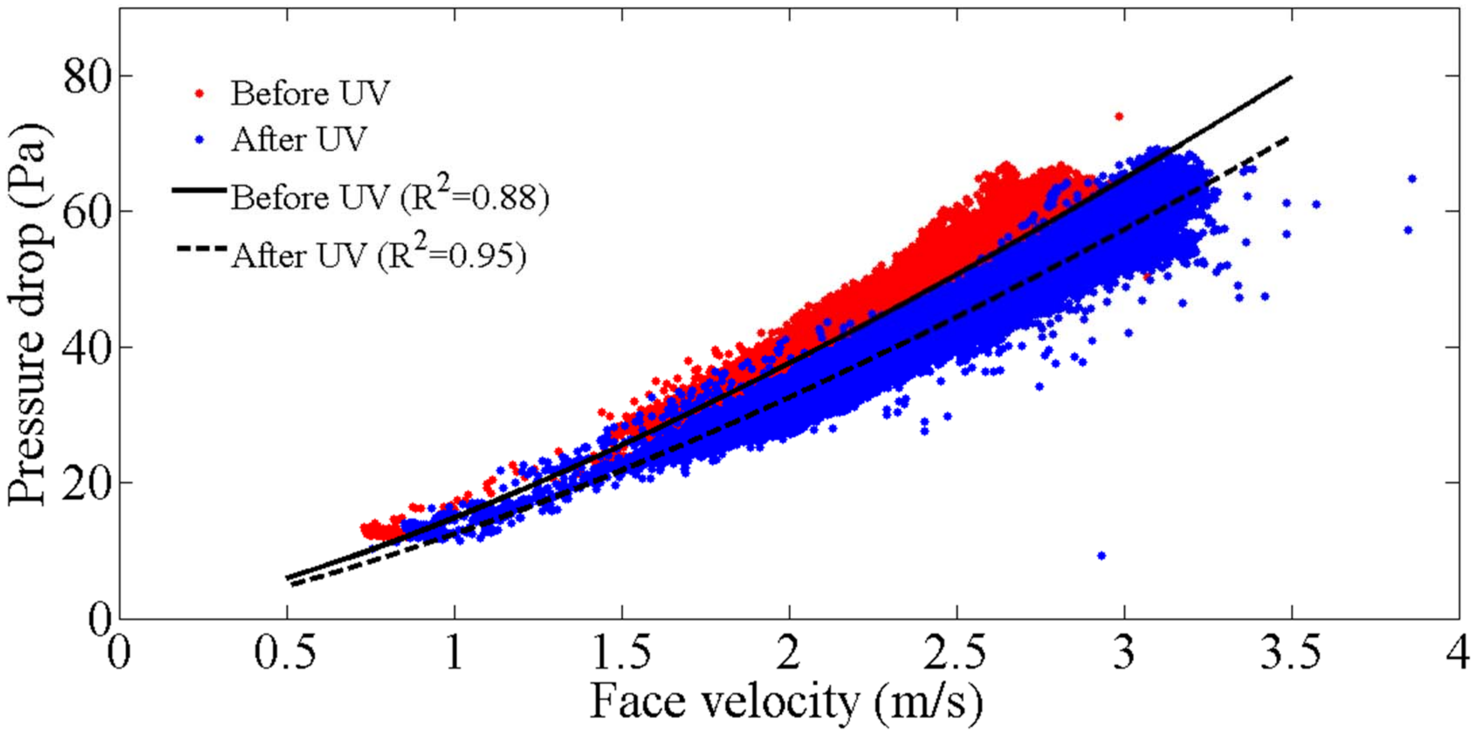
- Depending on application (flow conditions, disinfection goal), required fluence may be 100s of μW/cm^2
- In-duct system likely to require less lamp power than upper room system, however,
  - Cannot have an effective ventilation air change rate higher than supply air flow rate
  - May not be as effective at providing protection in a high-density occupancy
- Installation upstream of cooling coils should minimize power requirements/cost but may not be best if coil maintenance is also desired

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 (2017 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

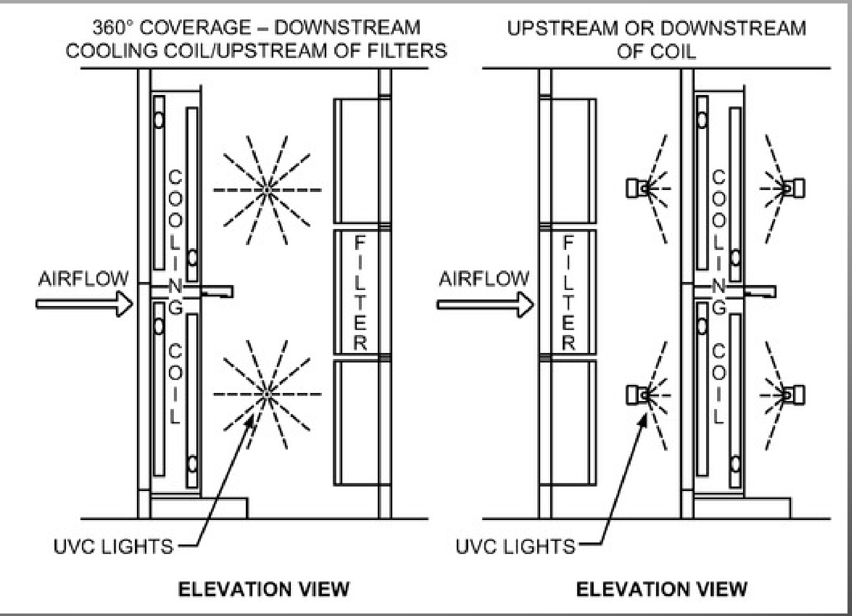
Yi, et al.—ΔP Reduction up to 15%

Singapore Laboratory



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
  - Is air disinfection a goal?

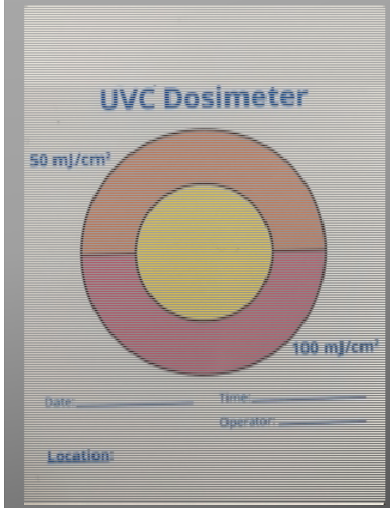


In-Room Surface Disinfection

- 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



Photodegradation of Materials

- Affected Materials
- ASHRAE RP-1509

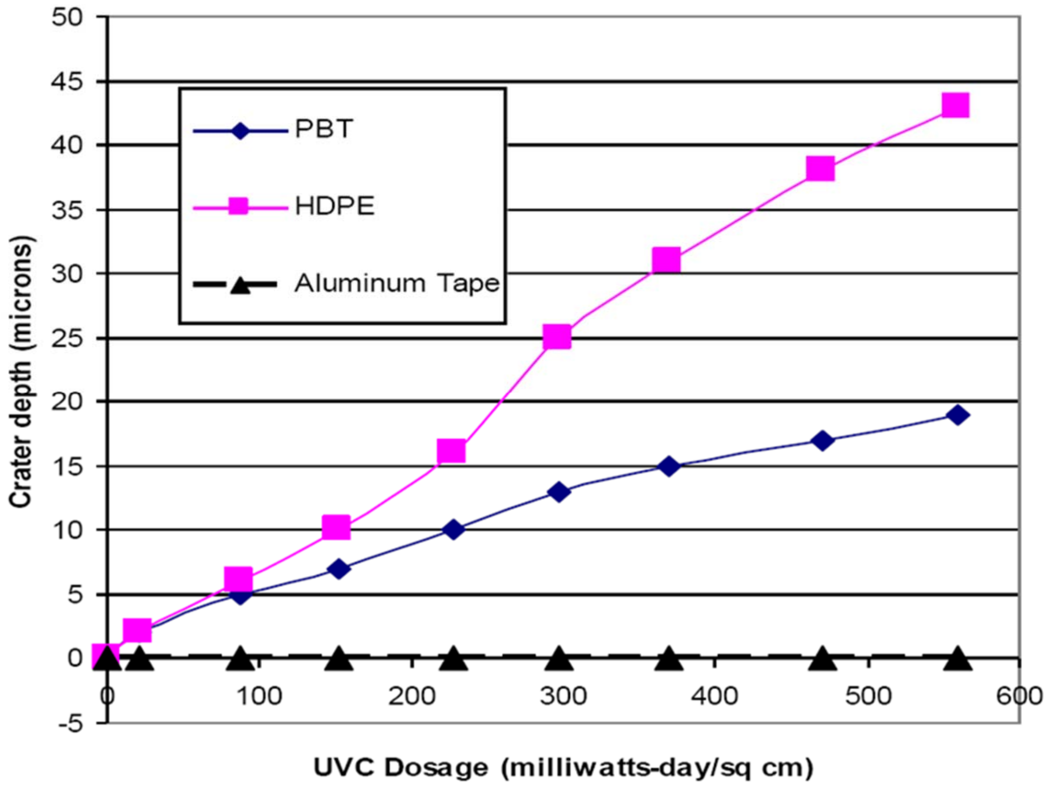
Affected Materials

- 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 $I \times t = \text{constant}$
- 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

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/cm^2 254 nm UVC:
  - 50 μm wire insulation loses 40% of mass
  - 1 cm panel loses ~0.2% of mass

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

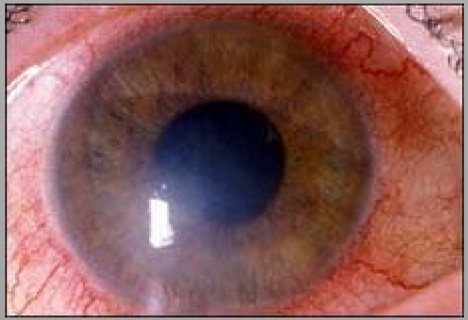
- Radiometer measurements
  - Confirm acceptable output level
  - Confirm acceptable occupied zone exposure for upper-air systems
- In-situ sensors may be considered for fault detection
  - Check relative output level after calibration by high-accuracy instrument
- Highly accurate measurements require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

UV Health and Safety Considerations

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

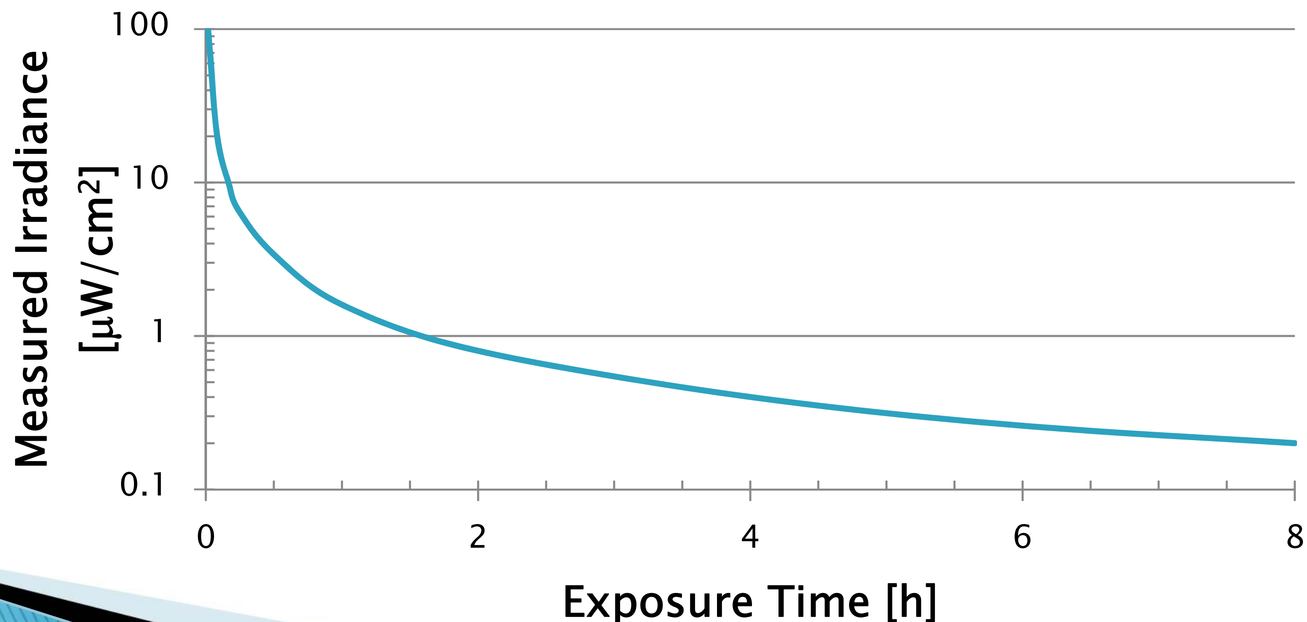
UV Exposure

- 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)



Exposure Limits

- NIOSH Limits for 253.7 nm UVC
  - 1 s: 600 μW/cm²
  - 1 min: 100 μW/cm²
  - 1 hour: 1.7 μW/cm²
  - 8 hours: 0.2 μW/cm² (standard for upper-air)
- In-duct systems may produce 1000-10,000 μW/cm²
- Safe exposure for in-duct range is ~10 s or less

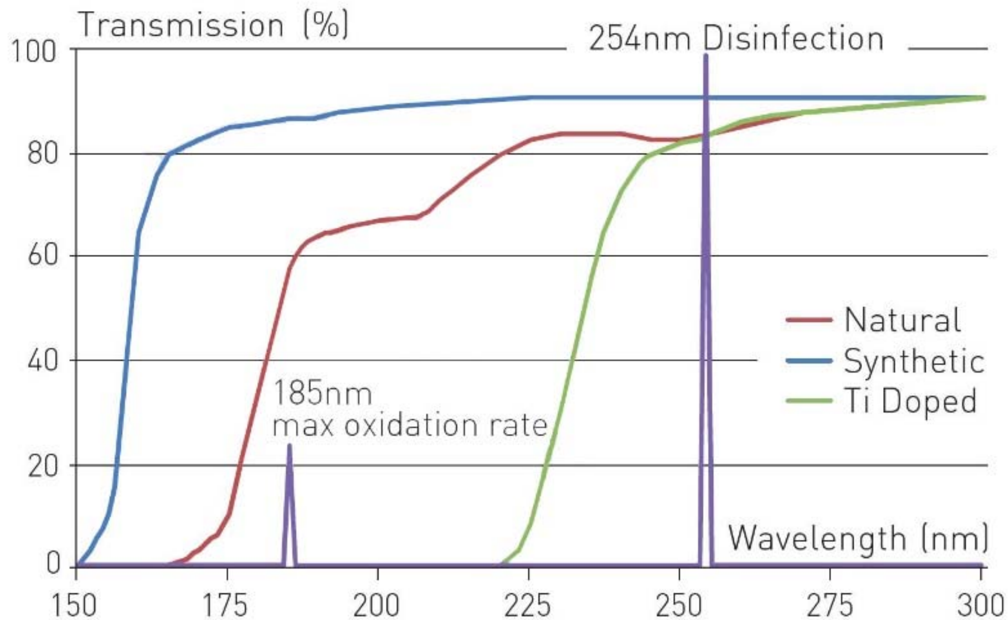


Ozone

- 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



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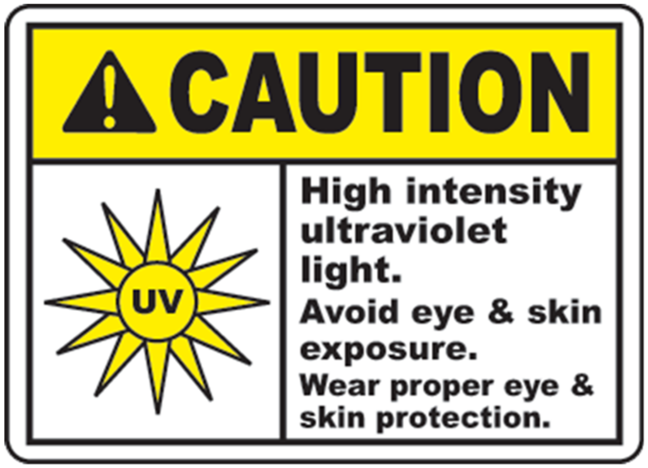
Protective Measures

- 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



Summary/Final Comments

- Disinfection of air and surfaces with germicidal light is a well-established technology with demonstrated effectiveness against many pathogens
- 254 nm UVC is the predominant wavelength today due to its high effectiveness and the availability of Hg vapor lamps
- UVGI can be applied to airstreams and surfaces in HVAC systems and to air and surfaces in spaces
- In application, care must be taken to limit human exposure and exposure of materials subject to photo-degradation
- UVGI is an adjunct to ventilation and filtration of particulate matter, not a replacement
- Emerging LED source technology will likely replace Hg lamps and result in use of other wavelengths and new applications

Basic References

- ASHRAE Handbook
  - 2016 HVAC Systems and Equipment, Ch. 17 *Ultraviolet Lamp Systems*
  - 2019 HVAC Applications, Ch. 62 *Ultraviolet Air and Surface Treatment*
- Martin, S., C. Dunn, J. Freihaut, W. Bahnfleth, J. Lau, A. Nedeljkovic-Davidovic. 2008. *Ultraviolet germicidal irradiation: current best practices*. ASHRAE Journal 50(8): 28-36.
- Bahnfleth, W. 2017. Cooling Coil Ultraviolet Germicidal Irradiation. ASHRAE Journal 59(10): 72-74.
- Kowalski, Wladyslaw. 2009. *Ultraviolet Germicidal Irradiation Handbook.* Berlin: Springer-Verlag Berlin Heidelberg.

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