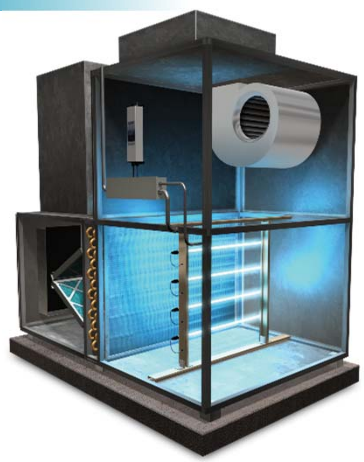
Reducing Infectious Disease Transmission with UVGI

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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.

[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.

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.*

Am. J. Hygiene (1942)

Reported Effectiveness Air Disinfection

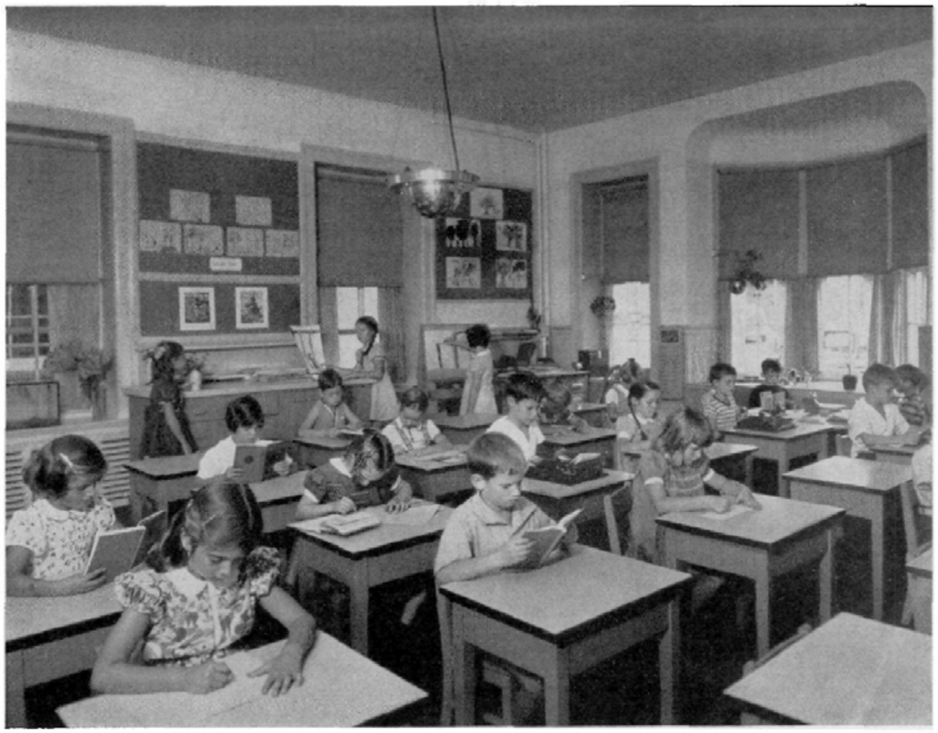
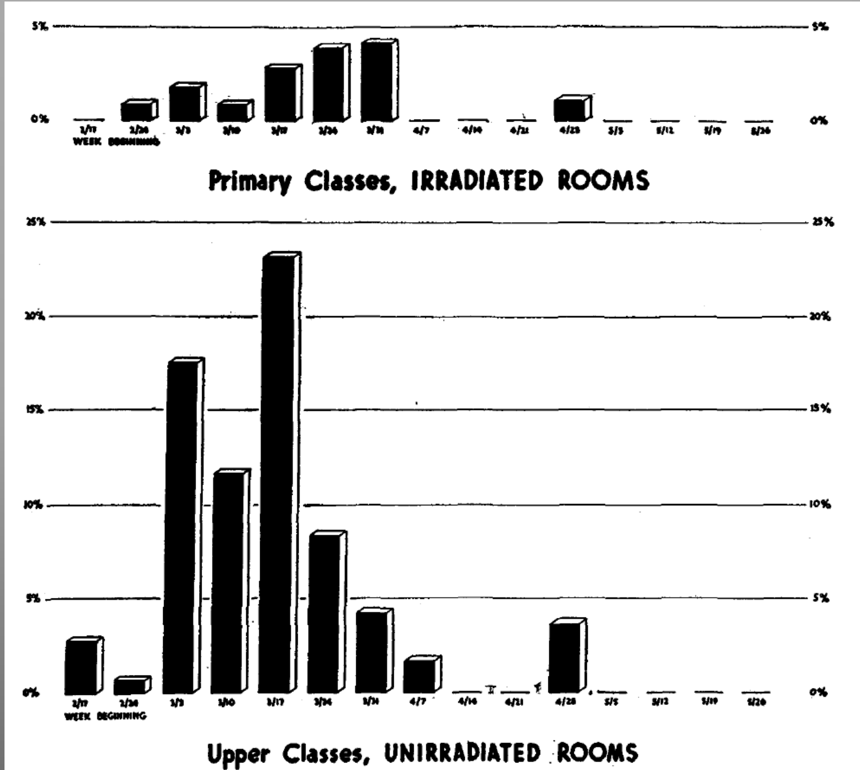


FIGURE 1. Classroom, Germantown Friends School, central radiant sources.



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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[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.

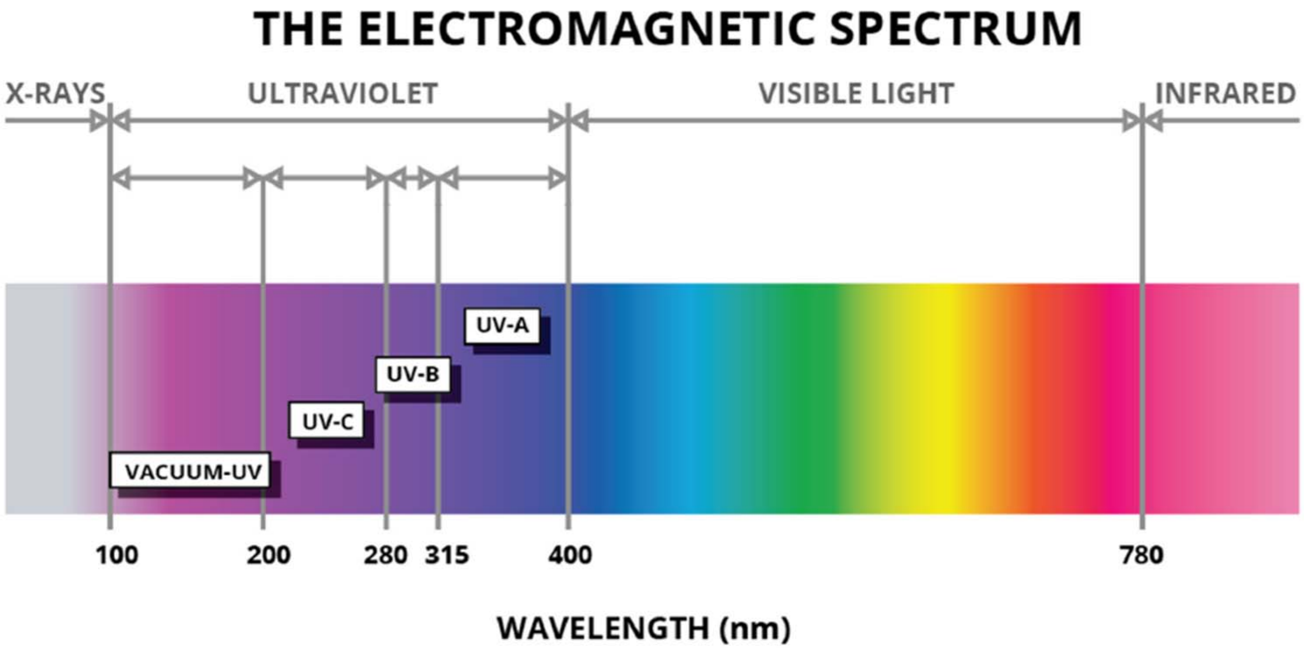
Outline

- 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

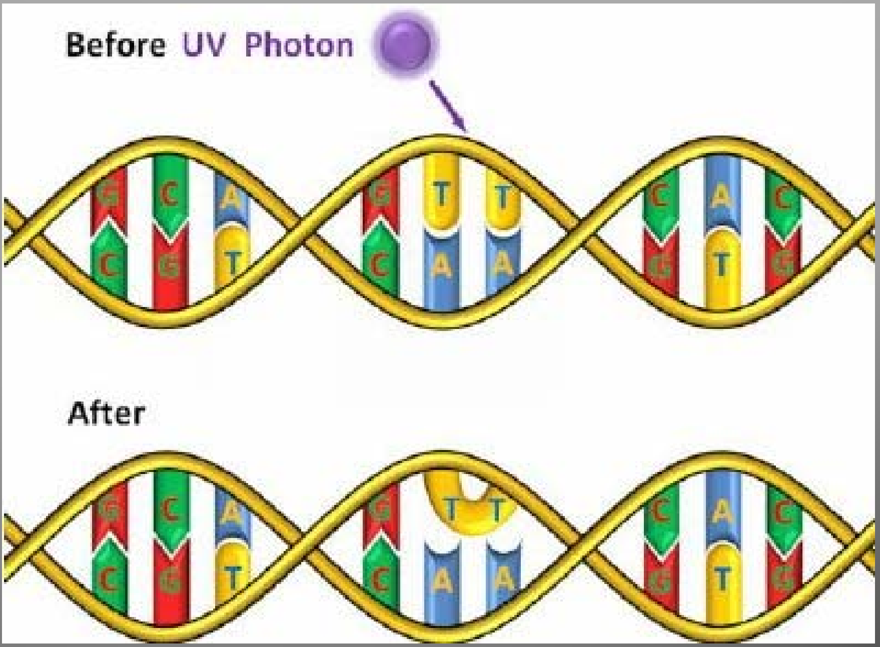
Optical Radiation (1 nm – 1mm)



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

Germicidal Action of UVC

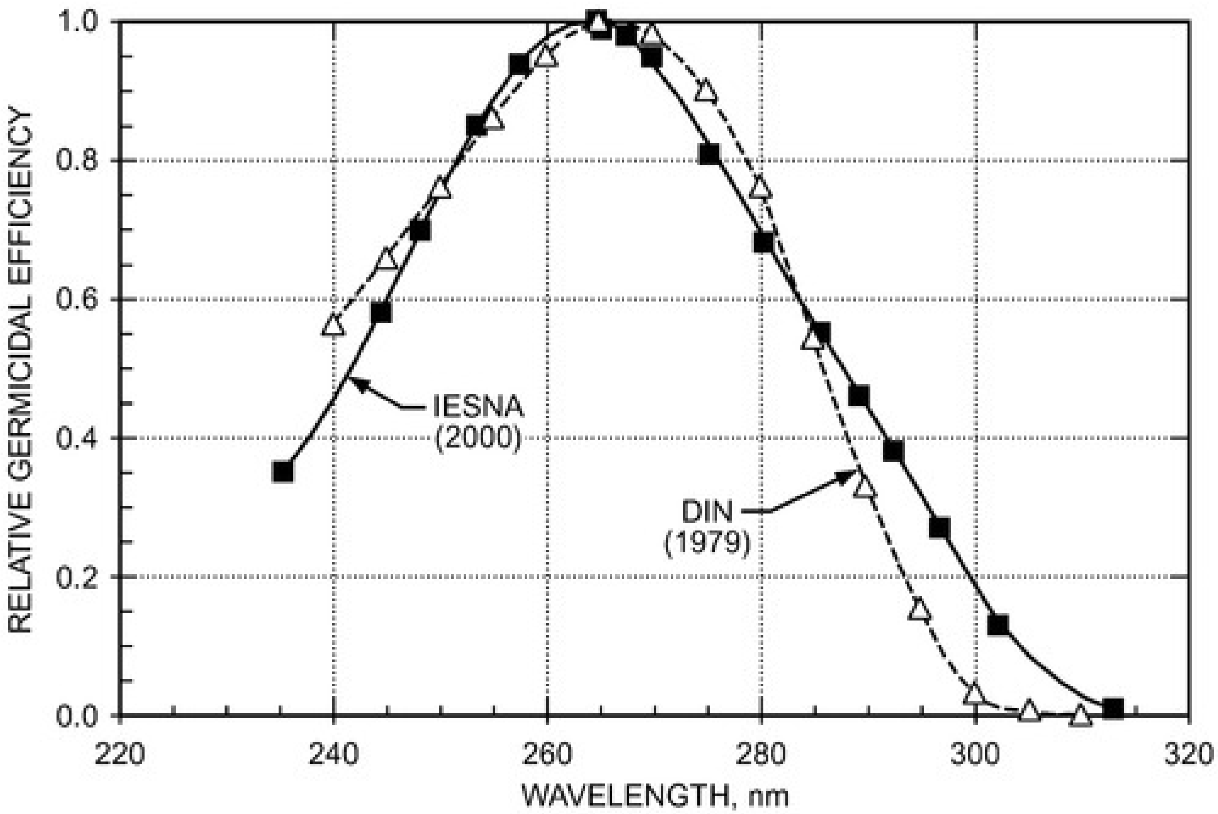
- UVC damages DNA/RNA of microorganisms (virus, bacteria, fungi)
- Microorganisms *inactivated*, i.e., become unable to replicate



Martin Hesseling, Hochschule Ulm

Germicidal Action Spectrum

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



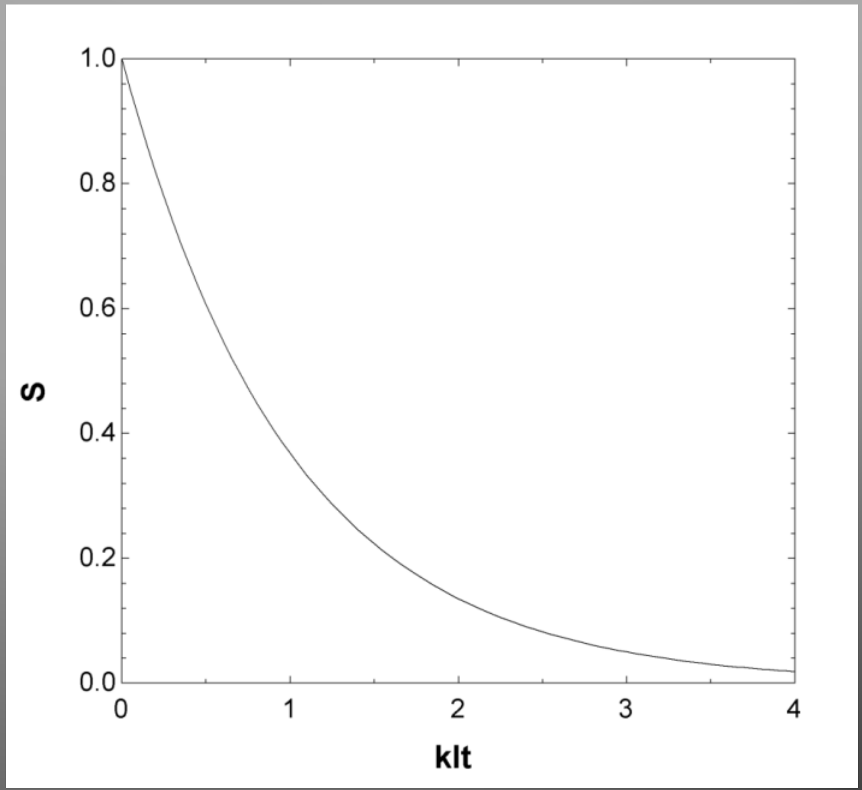
2019 *ASHRAE Handbook—HVAC Applications*, Ch. 60, Fig. 3

Microbial Dose Response to UVGI

- To a first approximation:

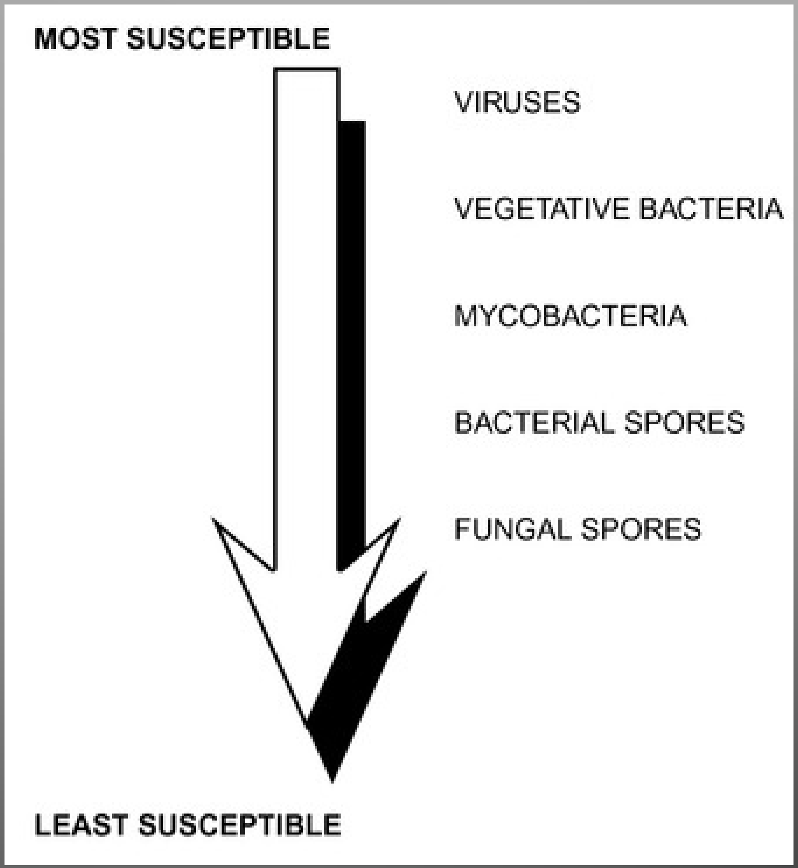
$$S = \exp(-kIt)$$
$$= \exp(-kD)$$

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



Microbial Response to UVGI – *k*

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

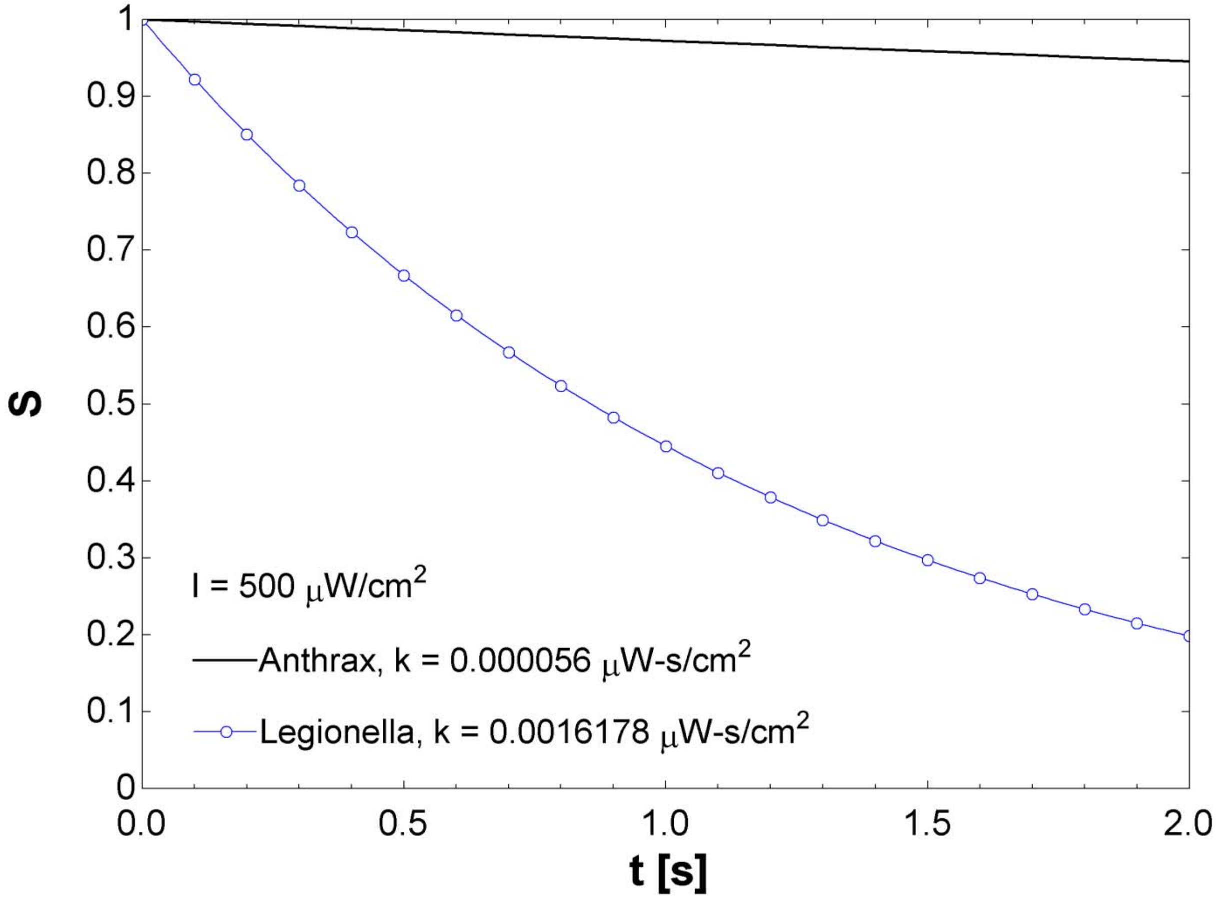


Representative Values ($cm^2/\mu W\text{-}s$)

- 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

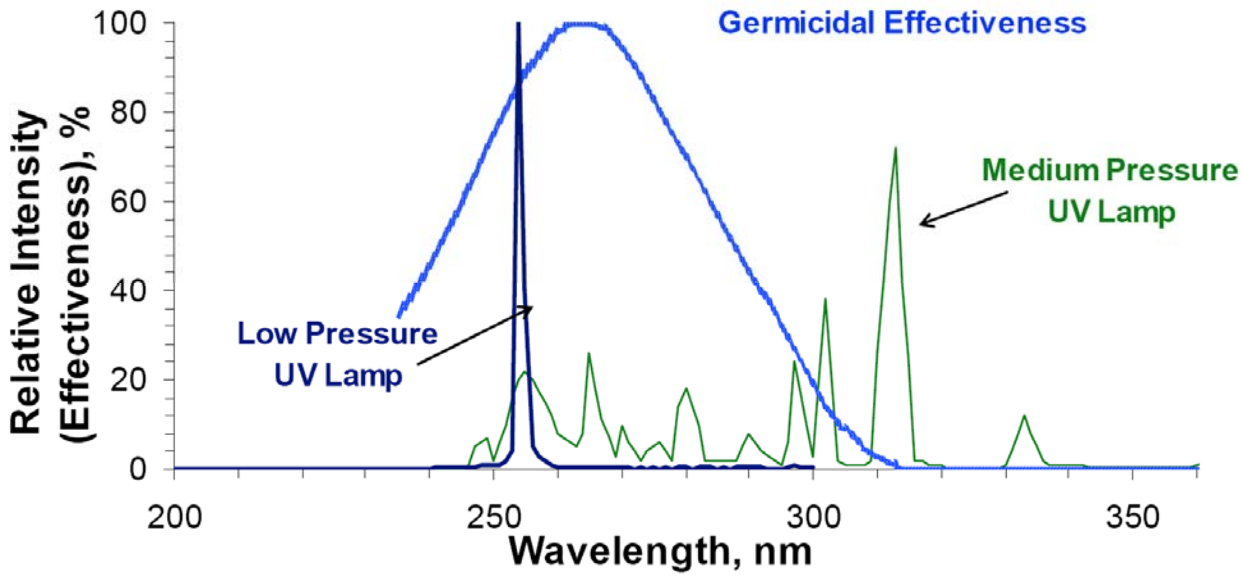


UVGI Equipment

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

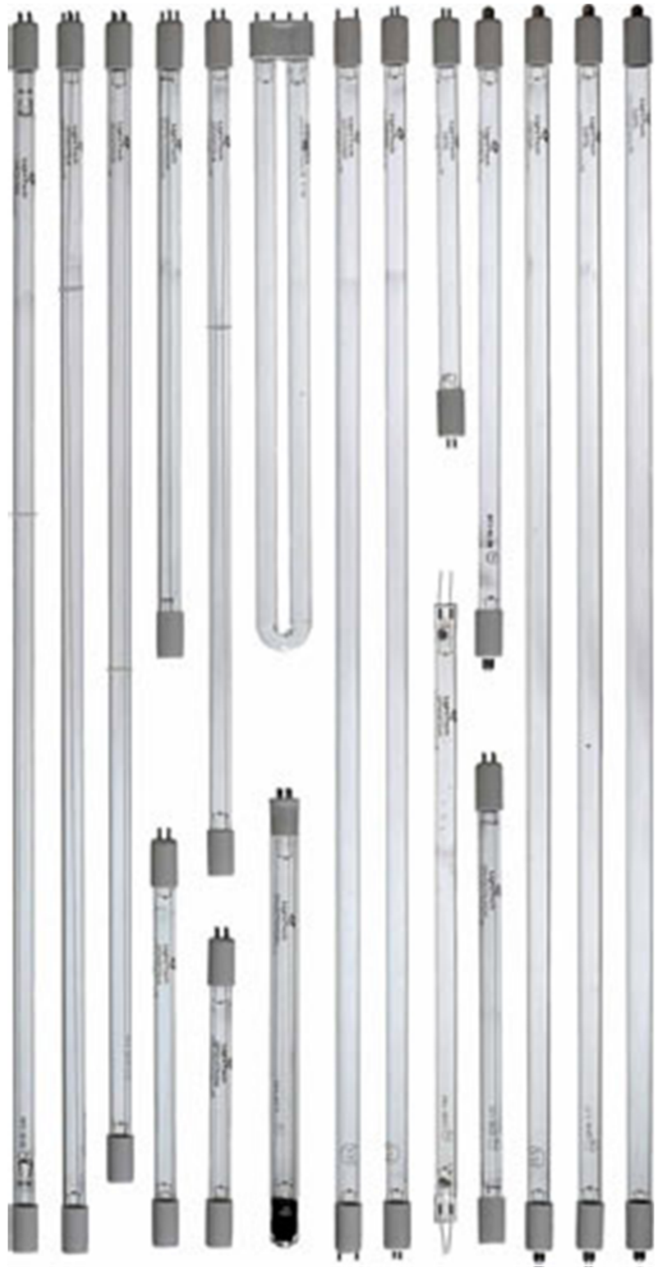
Lamps

- 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



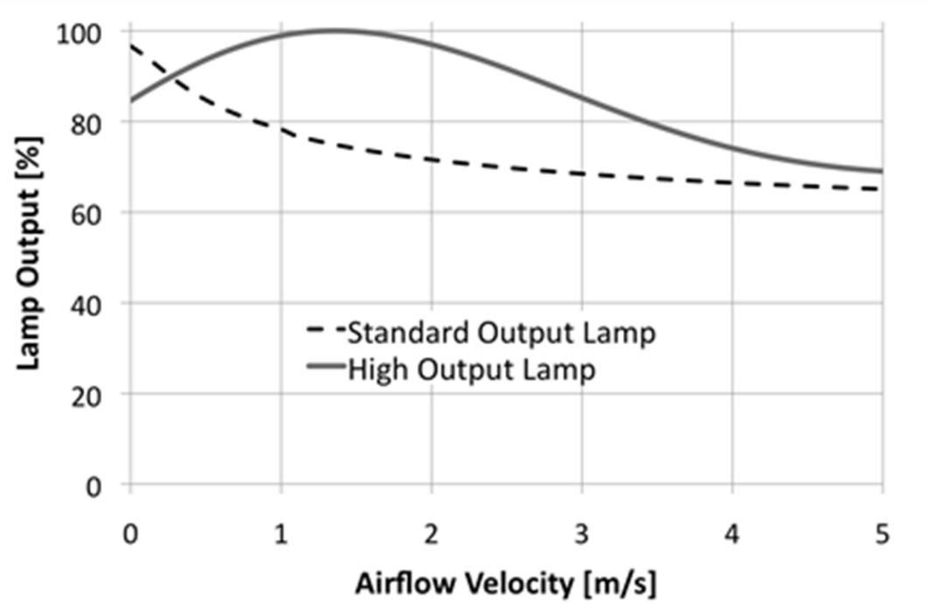
Lamps

- 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

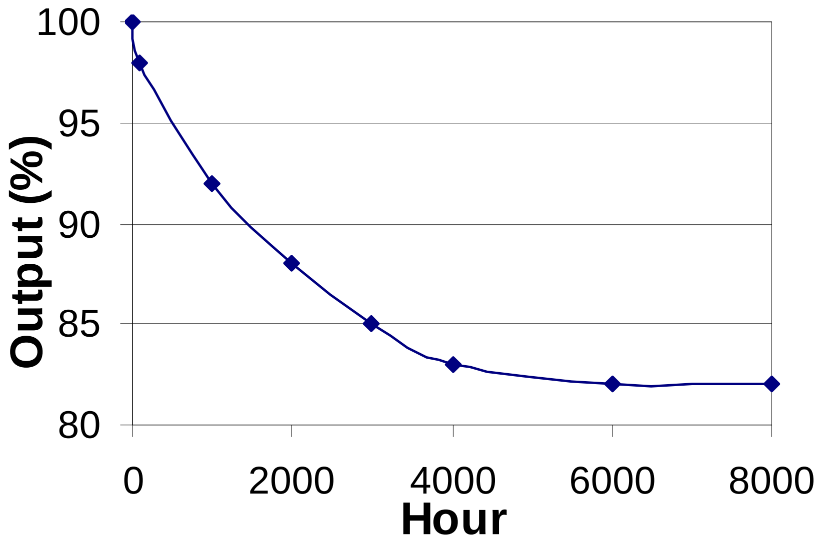
- Ballast = power supply
- Provides high starting voltage, then controls to safe operating current
- Ballasts should be matched with lamp per manufacturer's recommendations
- Starting mode
  - Preheat
  - Rapid start
  - Instant start
- Types
  - Magnetic
  - Electronic
- Dimming ballasts are available but not in common use

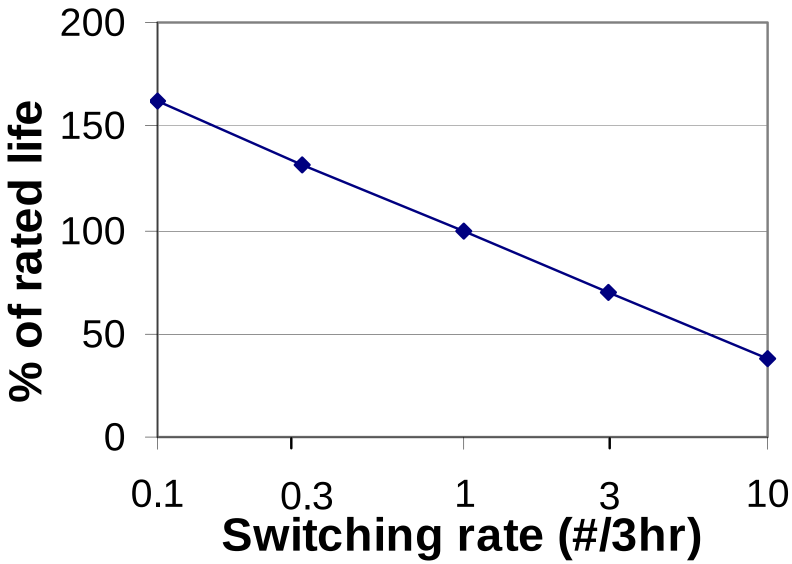
Impact of Ballast Selection on Lamp Performance

- 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





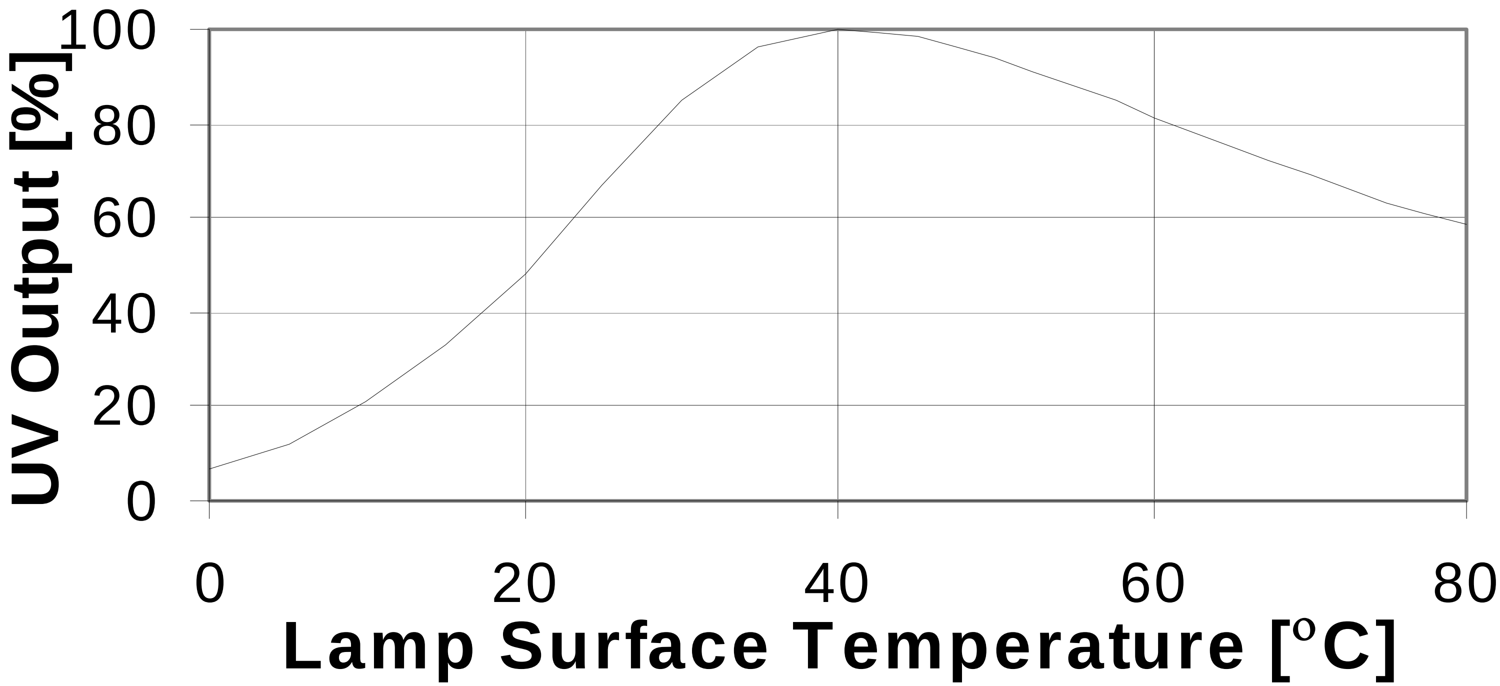
Depreciation

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

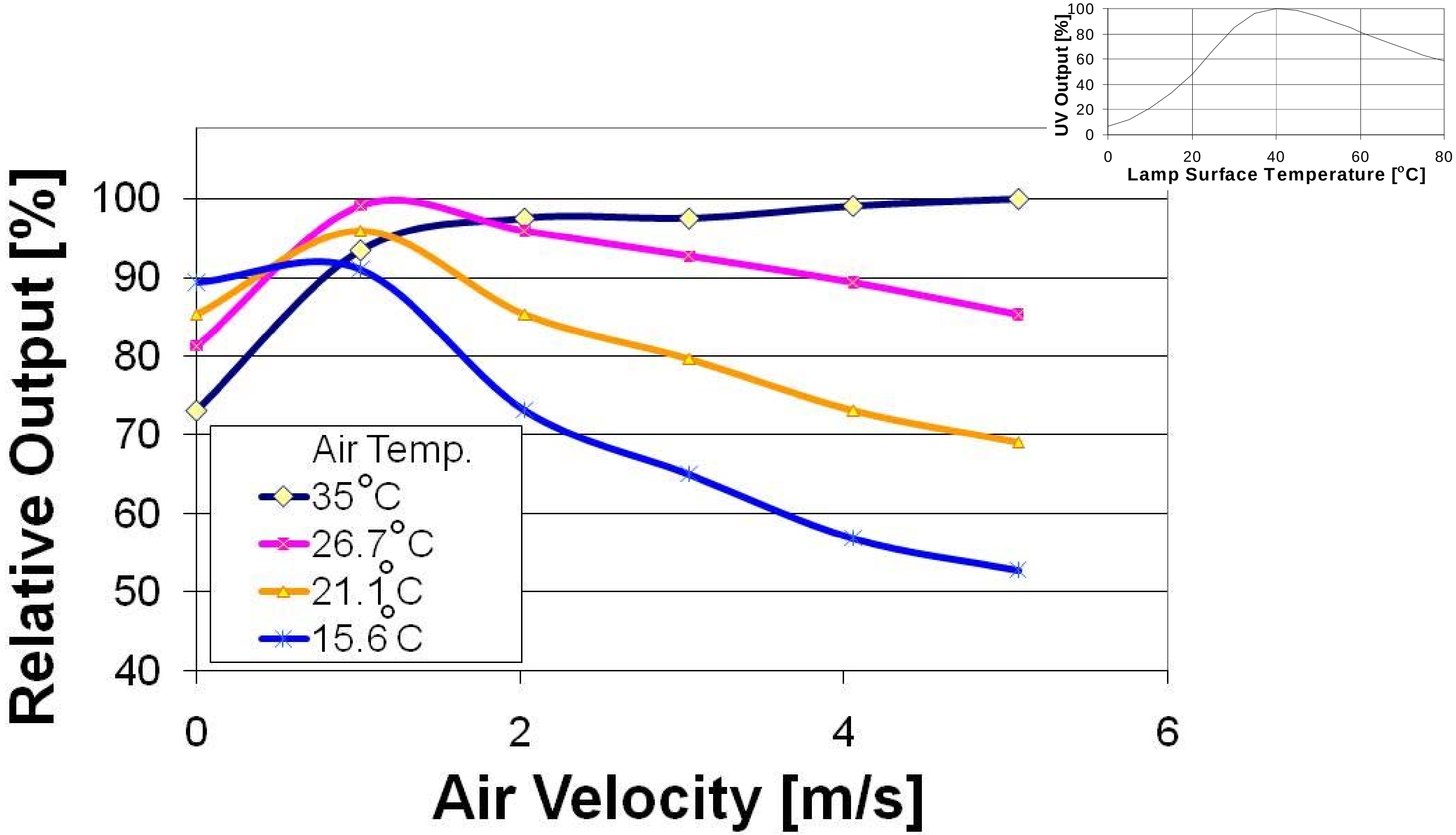
Typical Wind Chill Curve



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

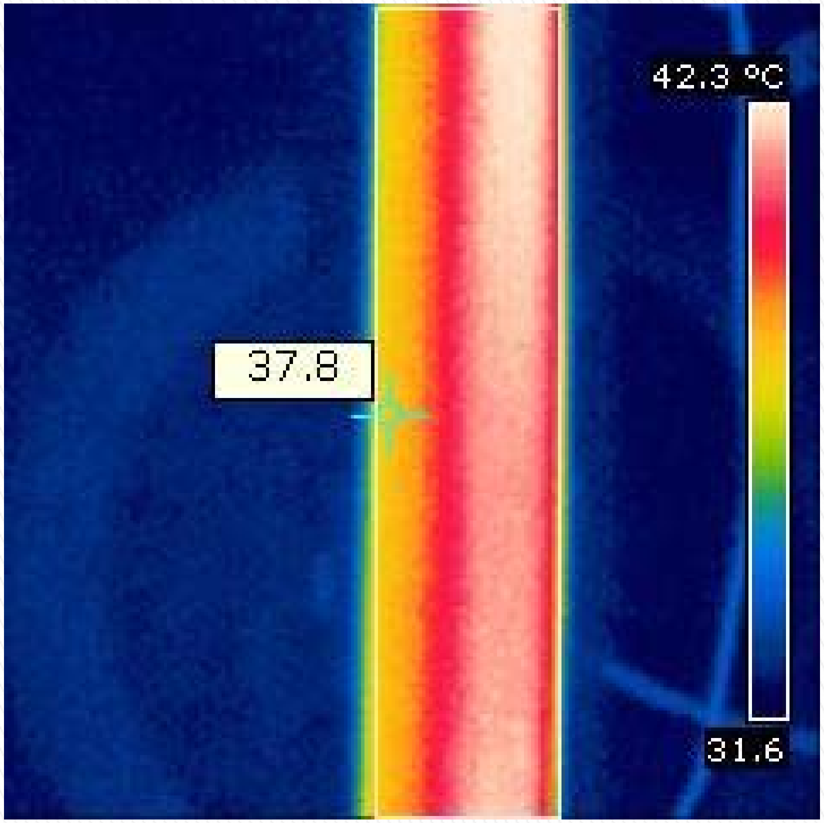
(Standard output lamp, cross flow)



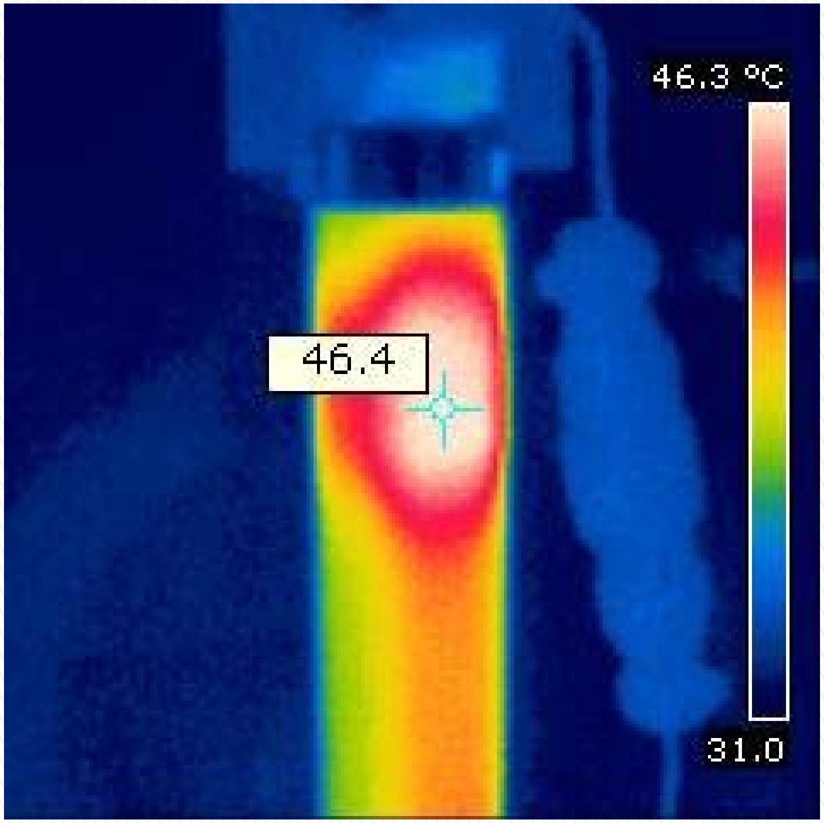
1 m/s = 196 ft/min, 15.6°C = 60°F, 35°C = 95°F

Temperature of Lamp in Cross Flow

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

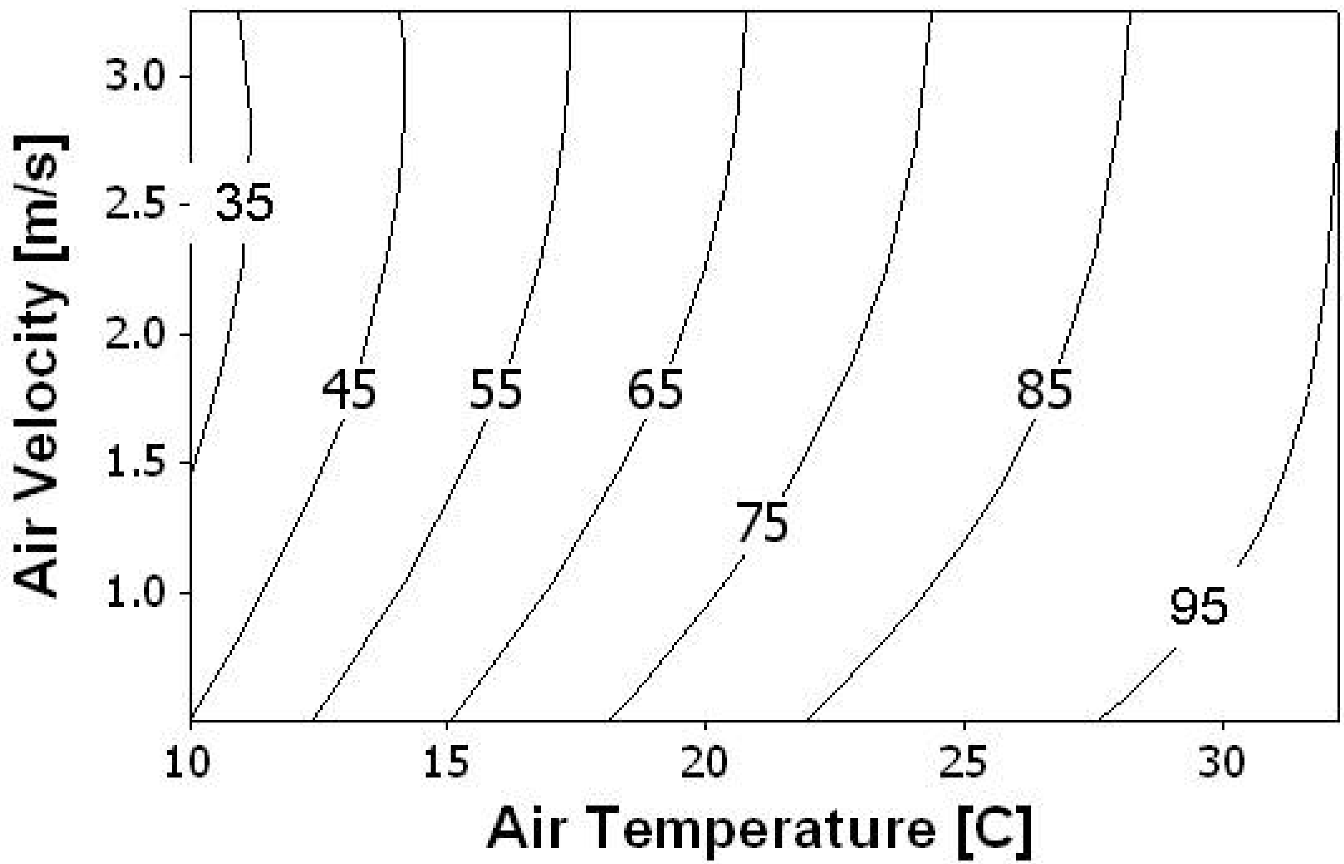


Center (flow left to right)



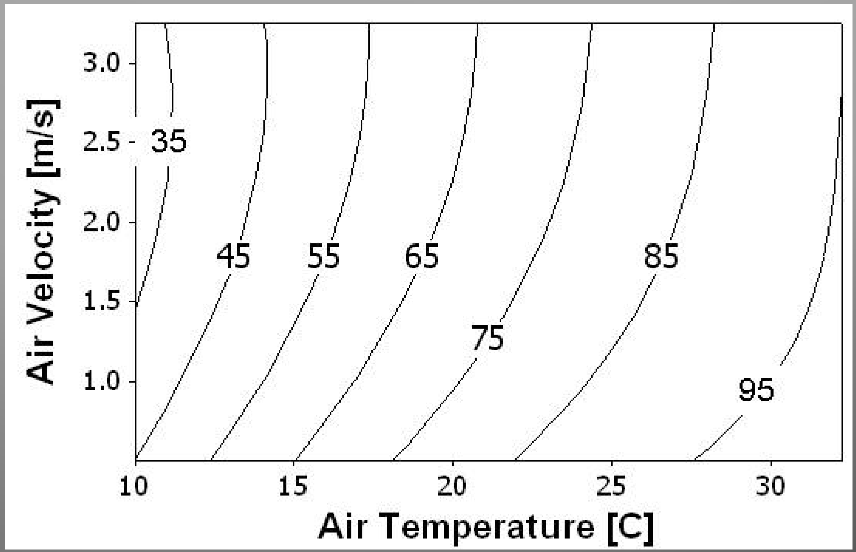
Socket end
(hot spot at cathode)

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

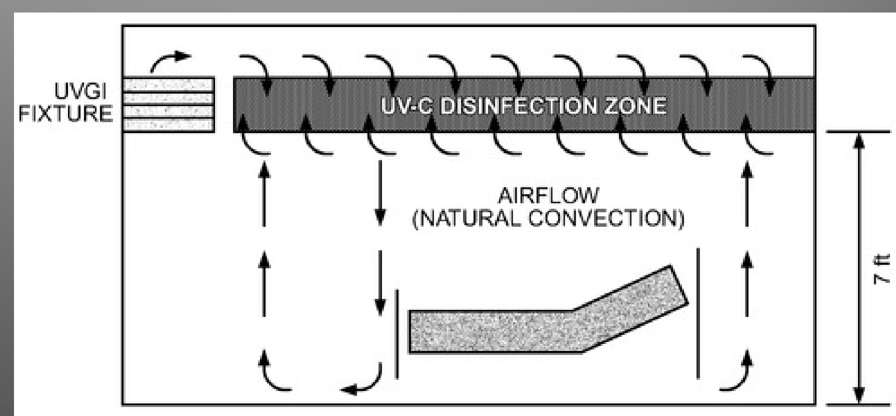


UVGI Applications and System Design Principles

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

Upper Room Disinfection

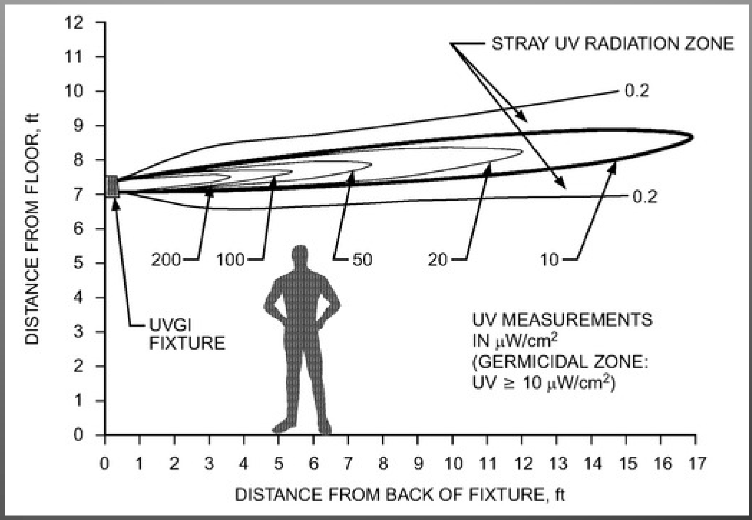
- Fixtures located above occupied zone
- Fixture directs UVC horizontally to create a disinfection zone
- Natural or forced air movement brings contaminated air into zone



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

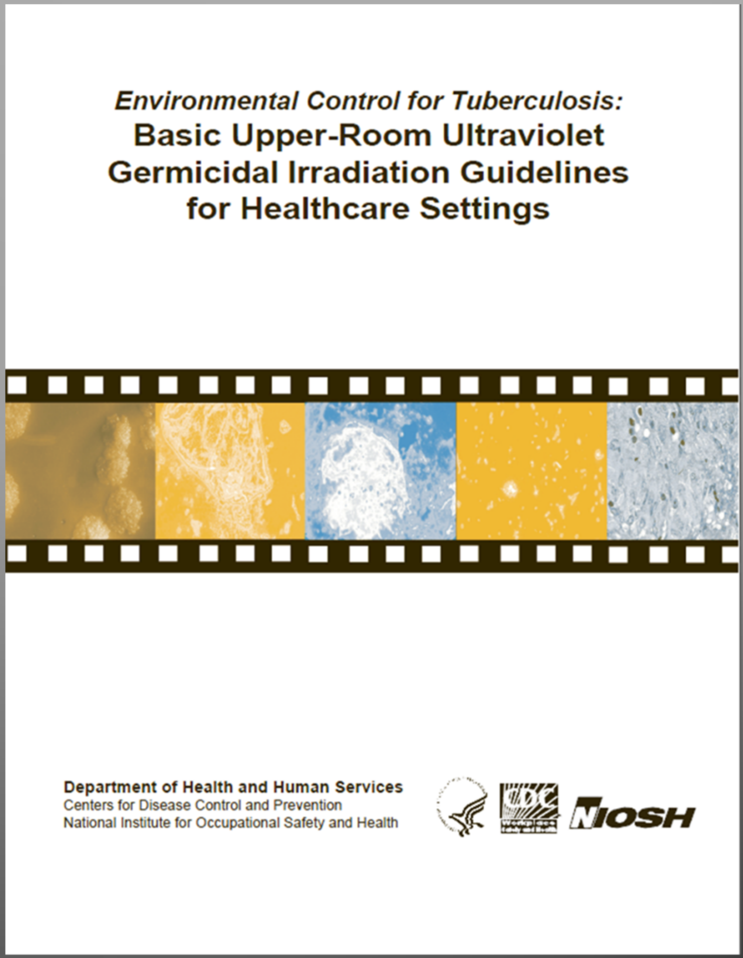
Upper Room Disinfection

- 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

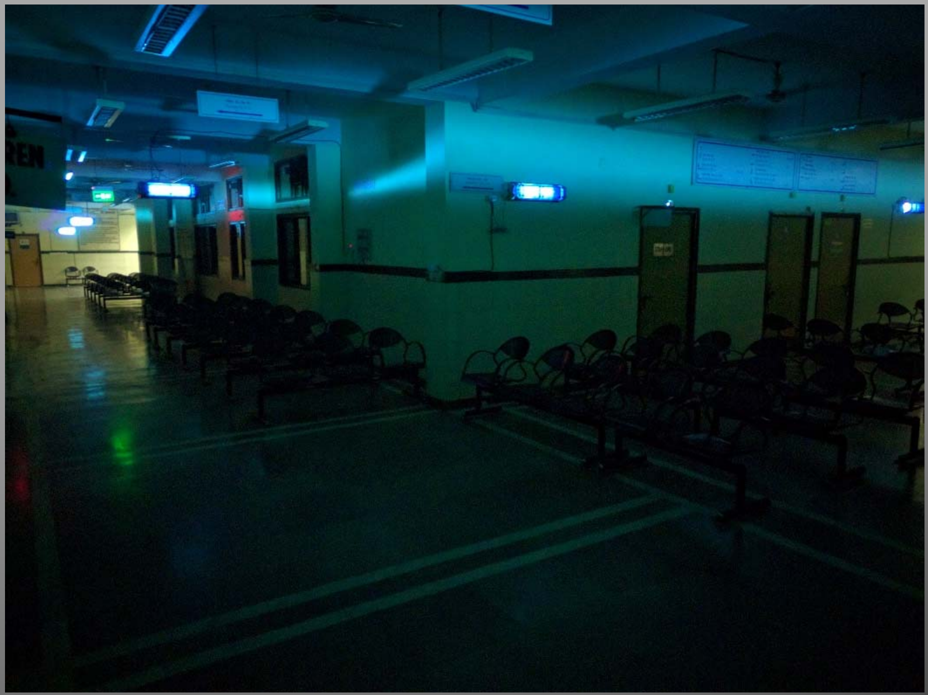
NIOSH (2009) Upper Room Design Guidelines

- 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



NIOSH (2009) Upper Room Design Guidelines

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

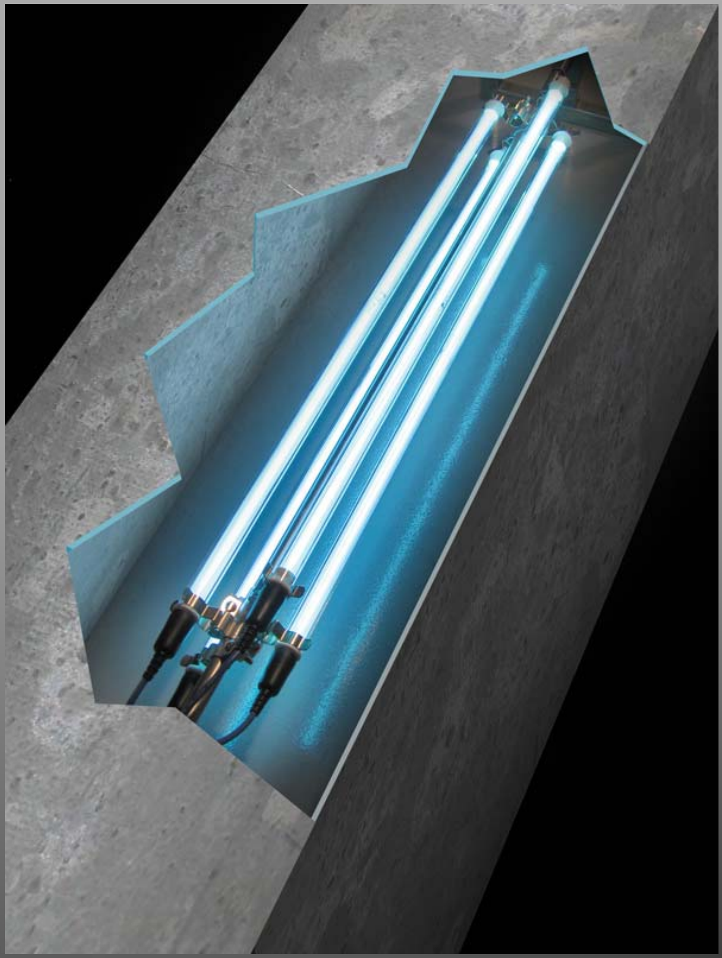


Portable UVGI Unit

- 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

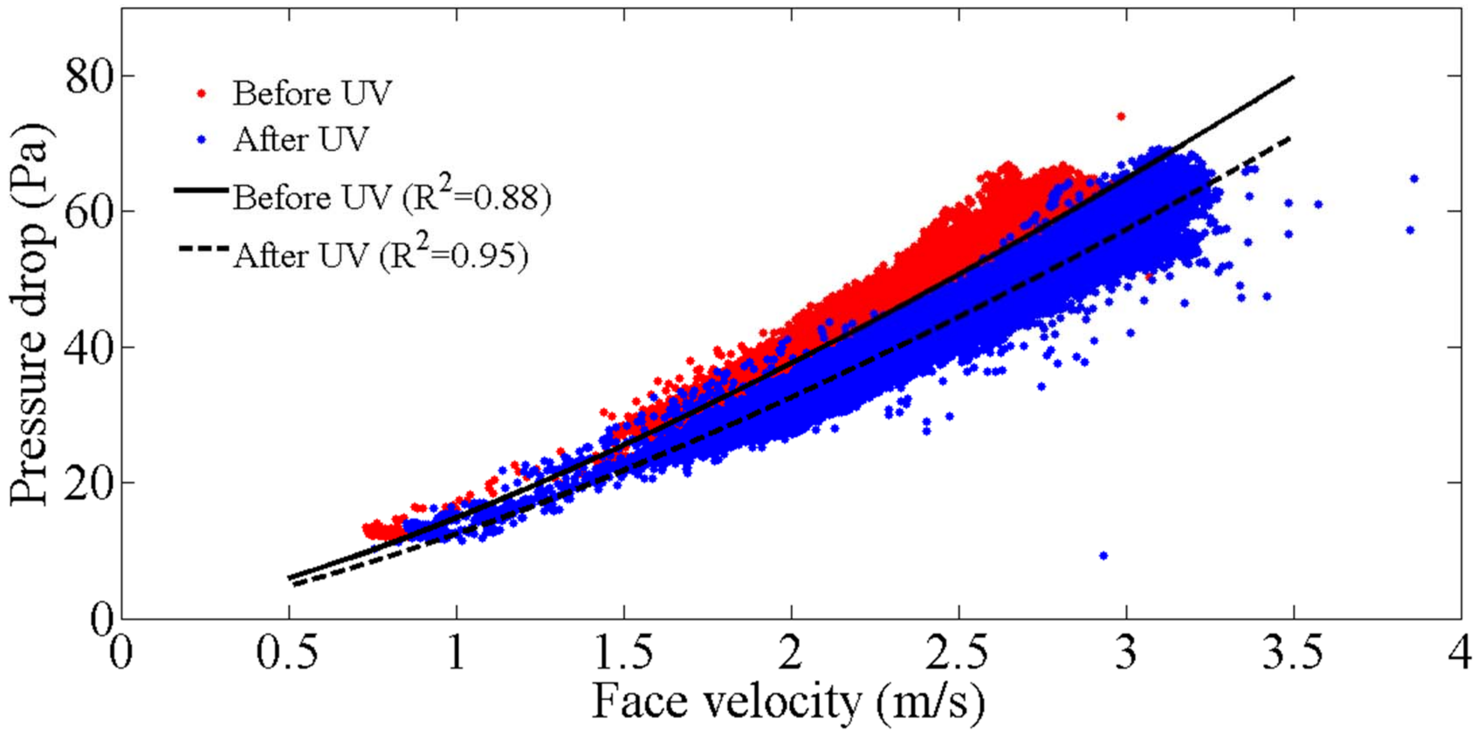
- Depending on application (flow conditions, disinfection goal), required fluence may be 100s of $\mu W/cm^2$
- In-duct system likely to require less lamp power than upper room system, however,
  - Cannot have an effective ventilation air change rate higher than supply air flow rate
  - May not be as 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

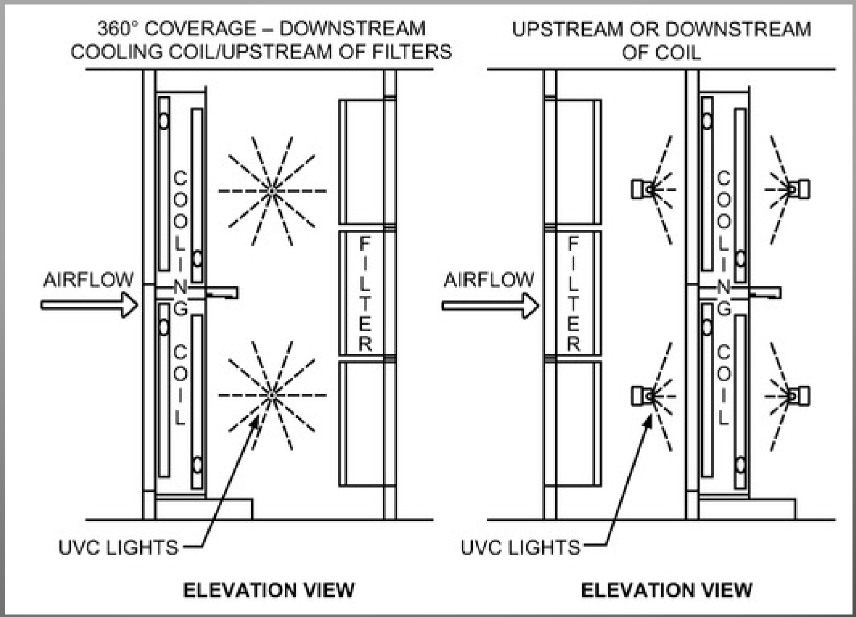
Yi, et al.—ΔP Reduction up to 15%

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?

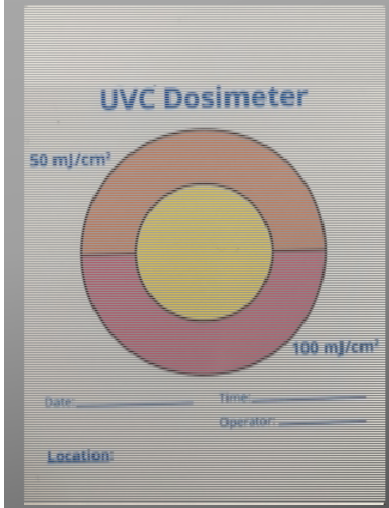


In-Room Surface Disinfection

- 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

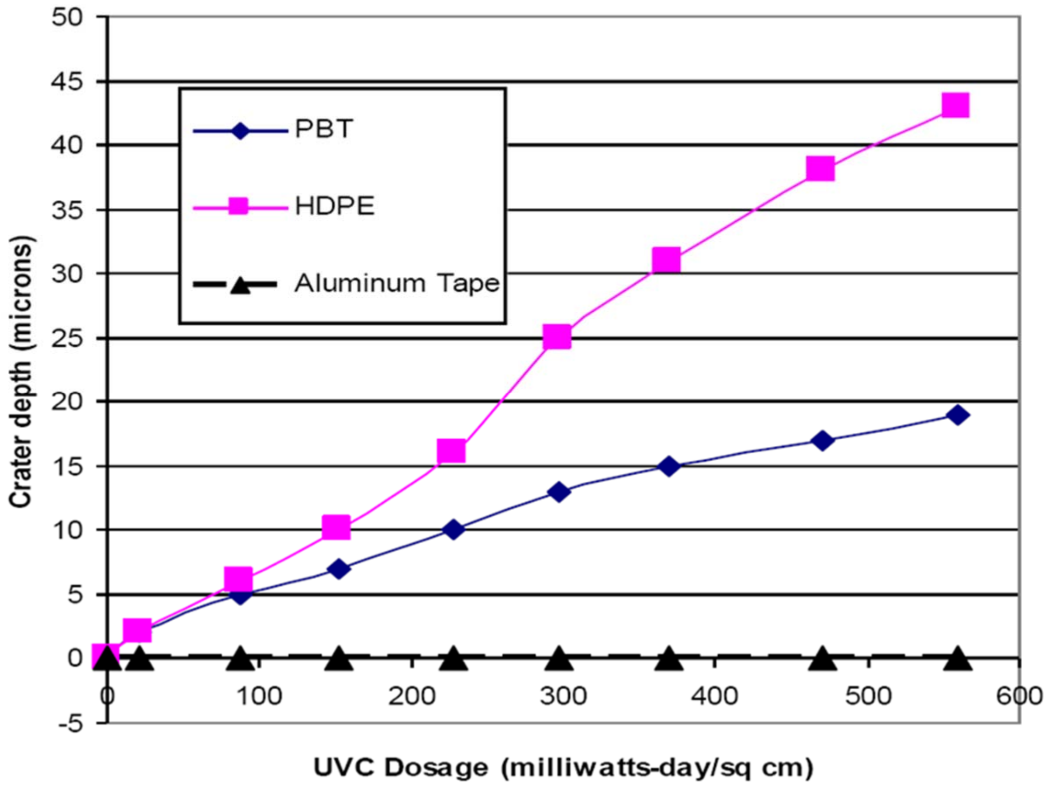
Affected Materials

- 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 $\mu m/cm^2$ 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

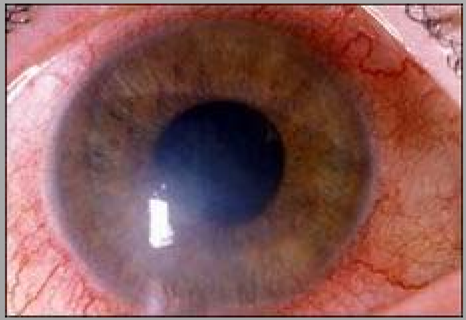
- Radiometer measurements
  - Confirm acceptable output level
  - Confirm acceptable occupied zone exposure for upper-air systems
- In-situ sensors may be considered for fault detection
  - Check relative output level after calibration by high-accuracy instrument
- Highly accurate measurements require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

UV Health and Safety Considerations

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

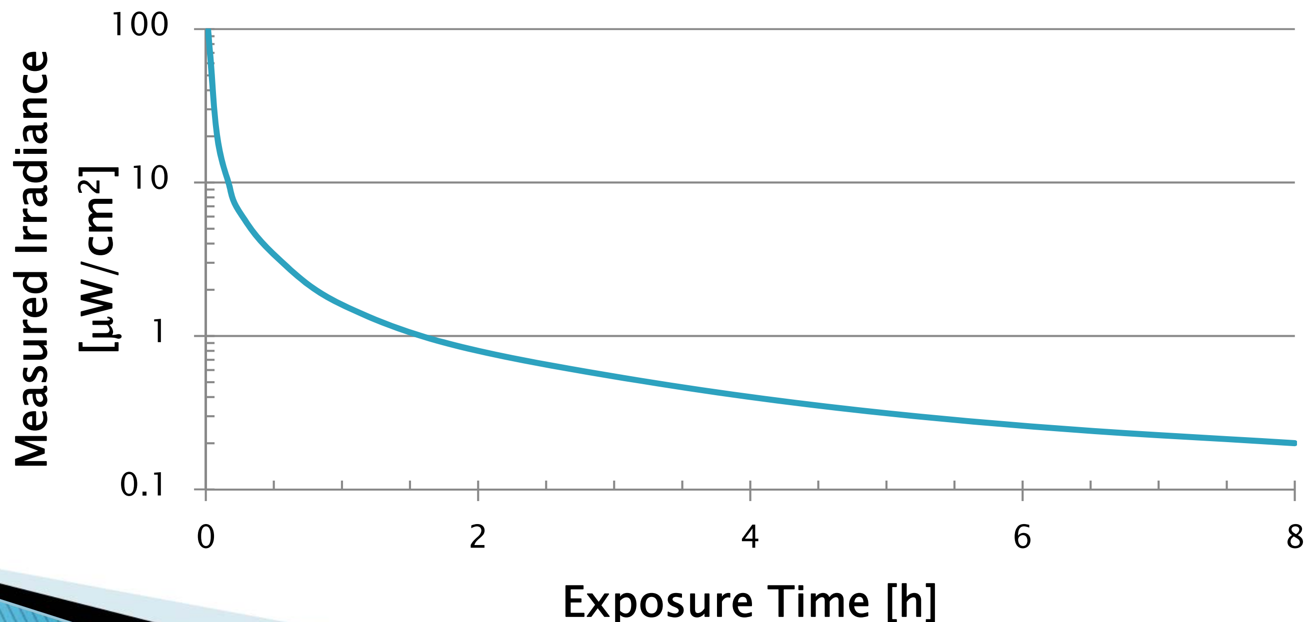
UV Exposure

- 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 $\mu W/cm^2$
  - 1 min: 100 $\mu W/cm^2$
  - 1 hour: 1.7 $\mu W/cm^2$
  - 8 hours: 0.2 $\mu W/cm^2$ (standard for upper-air)
- In-duct systems may produce 1000-10,000 $\mu W/cm^2$
- Safe exposure for in-duct range is ~10 s or less

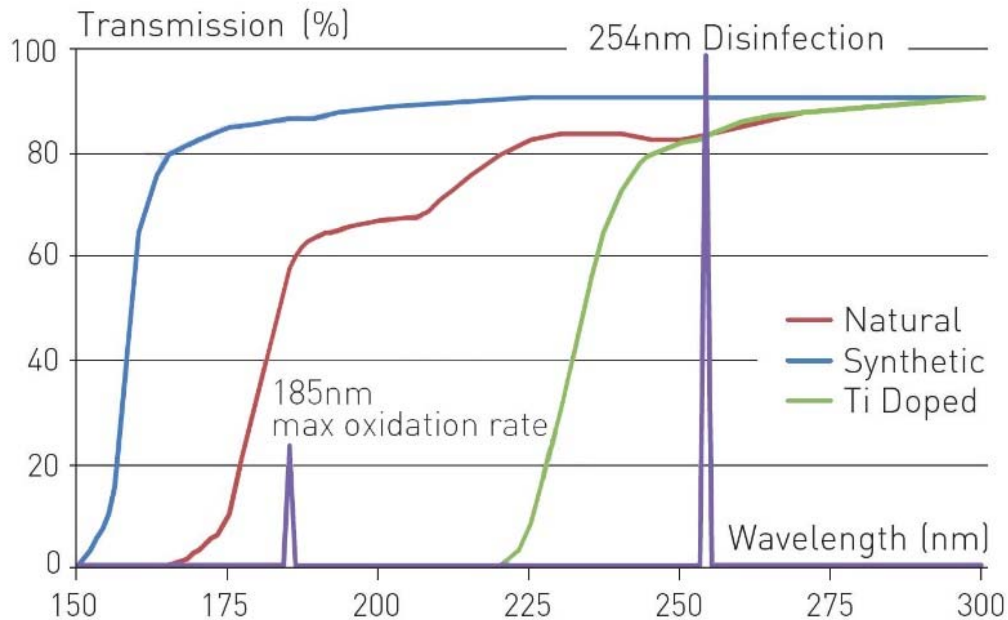


Ozone

- 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



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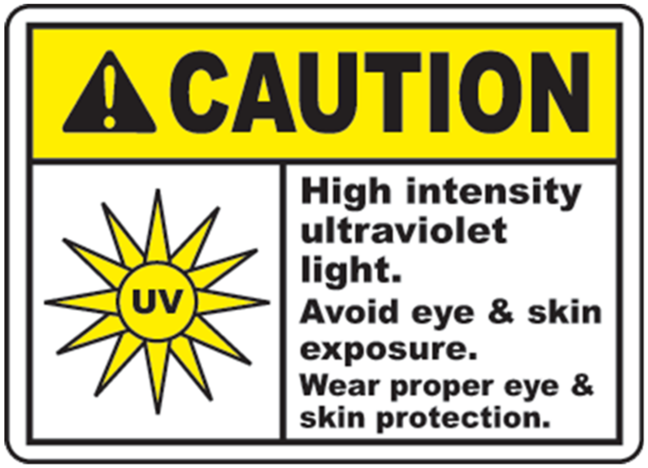
Protective Measures

- 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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