Bringing Sunshine Indoors:

Ultraviolet Germicidal Irradiation for Air and Surface Disinfection

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Outline

- UVGI Fundamentals
- UVGI System Types
- UV Degradation of Materials
- In-duct UVGI System Performance
- Summary

UVGI FUNDAMENTALS

- Ultraviolet germicidal irradiation (UVGI)
- UVGI history
- UV susceptibility and microbial dose response
- UV sources

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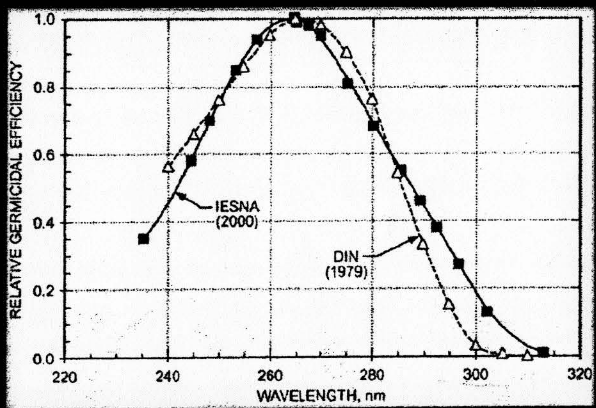
Ultraviolet Germicidal Irradiation

(UVGI)



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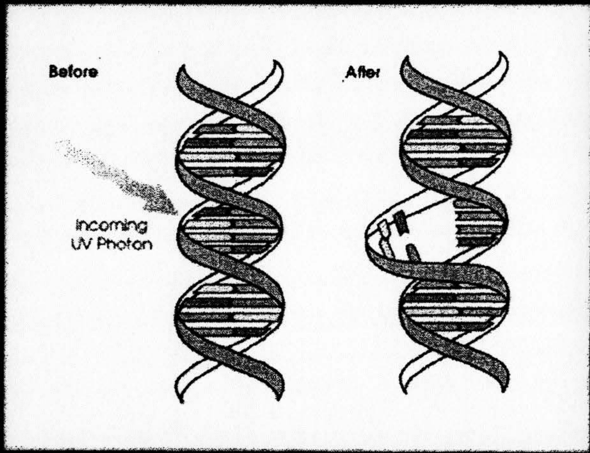
UV Dose and Microbial Response



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UVGI History

- 1880s Finsen uses UVB to treat skin diseases
- 1920s Studies of UV effect on microorganisms
- 1930s First UVGI air treatment applications - Wells, et al. Multi-year PA school study shows upper room highly effective against measles
- 1940s Studies of surface mold disinfection
- 1950s Use of UV in A/C described as "standard" application in GE literature
- 1980s First cooling coil disinfection Philips UV lamp application guidance
- 1990s Growth of commercial UVGI, renewed scientific interest in UVGI
- 2005 ASHRAE TG 2.UVAS formed
- 2007 TG 2.UVAS becomes TC 2.9 Ultraviolet Air and Surface Treatment
- 2008 ASHRAE Handbook-S&E chapter on UV
- 2009 ASHRAE Position Document on Airborne Infectious Diseases identifies UVGI as a proven technique for airborne infection control
- 2009 NIOSH guidelines for control of tuberculosis with upper room UVGI
- 2009 Formation of ISO working group on "UV devices"

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UV Dose and Microbial Response

- Effectiveness dependent on dose (D_{UV}, mJ/cm^2):

$$D_{UV} = It$$

I = average fluence rate or irradiance (mW/cm^2)

t = exposure time (s) [Note: 1 W = 1 J/s]

- Survival fraction (S)

$$S = \frac{N}{N_0}$$

N = number of viable organisms after UV exposure

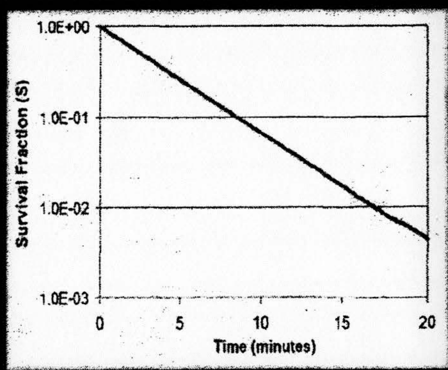
N_0 = number of viable organisms prior to UV exposure

UV Dose and Microbial Response

Simple Exponential Decay Model

$$S = e^{-kD_{UV}}$$

k = inactivation rate constant (cm^2/mJ)



UV Dose and Microbial Response

- k varies widely for different microorganisms (and even the same organism)
- Representative values (cm^2/mJ)
  - *Bacillus anthracis* 0.031
  - Influenza A 1.190
  - *Mycobacterium tuberculosis* 2.132
  - *Staphylococcus aureus* 3.476
- Accurate measurement of k is difficult and a weakness of existing design data

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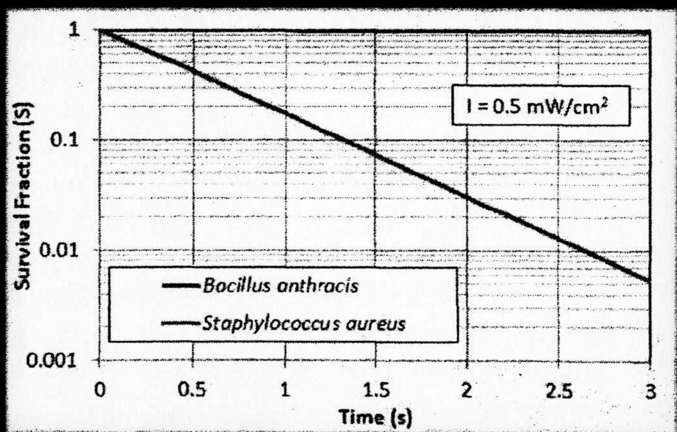
UV Dose and Microbial Response



- Filtration may be more effective for some microorganisms
- Consider multiple modes of air treatment

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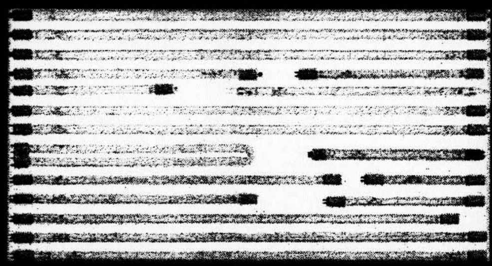
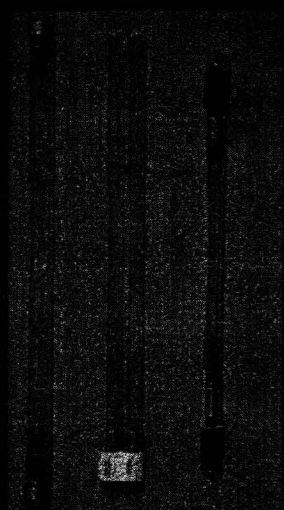
UVGI Sources

- Low-pressure Hg vapor lamps with quartz tubes produce nearly pure 253.7 nm UVC
- UVC output ~20-30% of input power

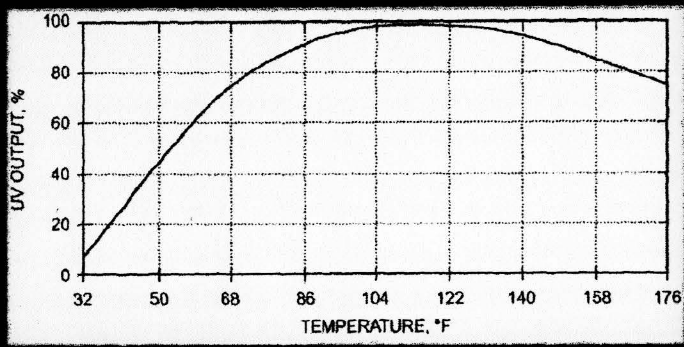


UVGI Sources

- Variety of sizes and shapes
- Output Level
  - Standard output (425 ma)
  - High output (800-1200 ma)
  - *High-output lamps operate at higher temperature than standard output lamps*
- Cathode
  - Hot cathode
    - Coated filament, thermo-ionic effect
    - Higher output than cold cathode
    - Starts affect life
  - Cold cathode
    - High voltage potential ionizes gas in lamp
    - Low power/output
    - Long life, not affected by starts



UL Lamp Output



Maximum output when cold spot T ~ 110°F

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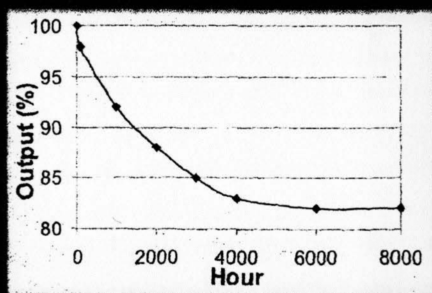
UV Lamp Depreciation and Life

- Output depreciates over time
- Increased on/off cycles decreases output faster
- Typical lifetimes:
  - Hot cathode
    - 6,000 to 13,000 hours
    - Most 8,000 to 9,000 hours
  - Cold cathode
    - Up to 20,000 hours



UVGI SYSTEM TYPES

- Room Decontamination
- Upper-Air
- In-Duct

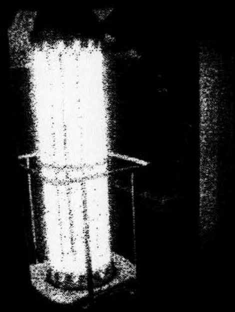
Room Decontamination

Surface Disinfection

- Portable
- Fully automated
- Built-in sensors measure reflected UVC surface dose, automatically terminate cycle
- Set for specific pathogens such as MRSA, *C. difficile*

Room Decontamination

Surface Disinfection



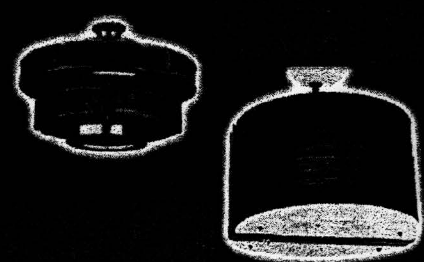
- >99.9% reduction of vegetative bacteria within 15 minutes
- 99.8% for C.*difficile* spores within 50 minutes

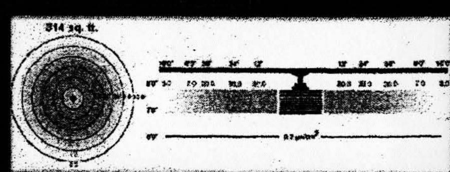
(Rutala et al. 2010)

Upper-Air UVGI

Air Disinfection

- Fixtures on walls or ceiling above 7 feet
- Consider when:
  - No mechanical ventilation
  - Limited mechanical ventilation
  - High-risk areas
  - Economics/other





Upper-Air UVGI

Air Disinfection

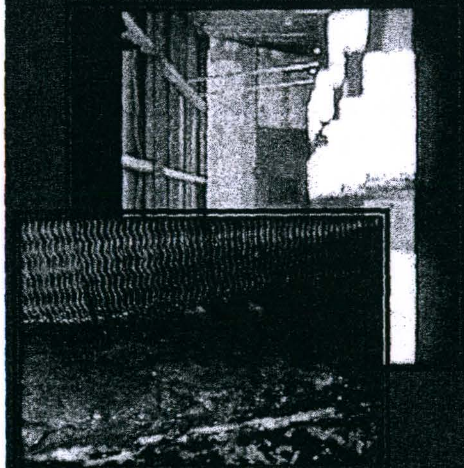
- 30W fixture per 200 ft^2
- Overlapping irradiance zone of 30-50 $\mu W/cm^2$
- Low reflectivity of walls and ceilings
- Ventilation should maximize air mixing
- Use fans where ventilation is insufficient

In-Duct UVGI

- Surface disinfection
  - Cooling coils
  - Drain pans
  - Others
- Air disinfection
  - "On-the-fly" inactivation

In-Duct UVGI

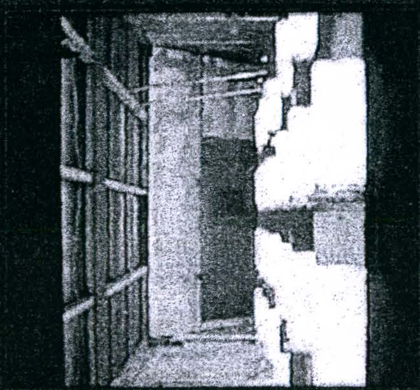
Surface Disinfection



- Upstream or downstream of the coil
- Even UV distribution across entire coil face
- 12 to 36 inches from coil face
- Operated 24/7

In-Duct UVGI Systems

Air Disinfection

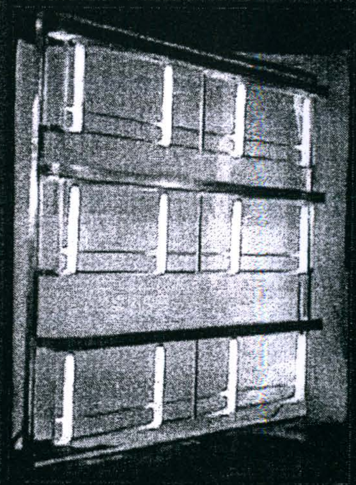


- Similar to surface disinfection
  - No reflectors
  - More lamps
- Return or supply plenum
- Various orientations
- Operated 24/7 or intermittently

In-Duct UVGI

Air Disinfection

- Dose is important!
- Systems designed for 500 fpm
- Limited exposure time (travels 1 foot in 0.12 seconds)
- Increased irradiance
- Minimum of 2 ft irradiation zone
- Rule of thumb: 0.25 second exposure



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In-Duct UVGI

In Conjunction with Filtration

- Should always be coupled with filtration
- MERV 6-8 appropriate for dust control
- Highest practical MERV filter recommended
- Enhanced air cleaning with increased filtration

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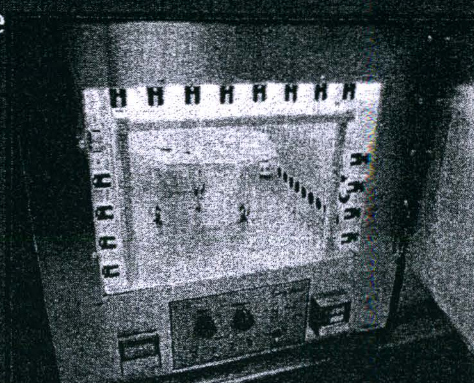
UV DEGRADATION OF MATERIALS

- ASHRAE Research Project 1509
  - Dr. Robert E. Kauffman
  - University of Dayton Research Institute

UV Degradation of Materials

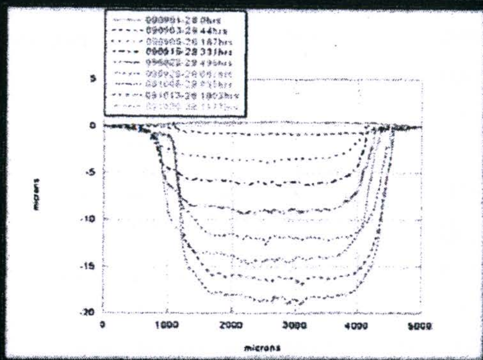
Photoreactor

- Commercially-available UV reactor with rotating platform
- ½-inch circlular samples of materials
  - Polished smooth
  - Aluminum collars exposed only center 1/8-inch circle to UV energy



UV Degradation of Materials

Profilometer



- Stylus profilometer to measure mass loss (crater depth)
- Compared UV-exposed surface to polished surface

UV Degradation of Materials

Degradation Rankings

A – No Effect (inorganic materials; all organic materials exhibit some degradation)

B – Minor Effect (mainly cosmetic changes – not likely to affect ability to perform its duty)

C – Moderate Effect (some cracking/pitting suggesting the need for shielding)

D – Severe Effect (structural damage, not recommended)

UV Degradation of Materials

Polymers

Rating B	Rating C	Rating D
Formvar	Polyimide	Acrylic
Nylon Black	LDPE	PET
Natural Nylon	ABS	PBT
Perfluoroethylene	Cast Epoxy	Polypropylene
	Polyvinyl Chloride	HDPE
	Polycarbonate	Polyacetal
	Phenolic Resin	

IN-DUCT UVGI SYSTEM PERFORMANCE

- Two papers at the 11th International Building Performance Simulation Association Conference, Glasgow, Scotland, July 2009
  - Bahnfleth et al., *Annual simulation of in-duct ultraviolet germicidal irradiation system performance*
  - Lee et al., *Life-cycle cost simulation of in-duct ultraviolet germicidal irradiation systems*

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Simulation-Based LCC Analysis

- Performance simulation
  - Thermal/energy (whole-building—eQUEST/DOE2)
  - 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

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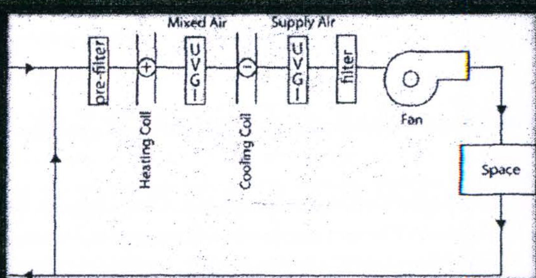
Example-Office Building

- New York City
- 4 floors @ 25,600 ft^2
- 1 VAV system/floor
  - 17,000 CFM SA, 3800 CFM OA
  - 50°F SAT, 500 ft/min, MERV 6 filtration (base)
- One system on a middle floor studied in detail



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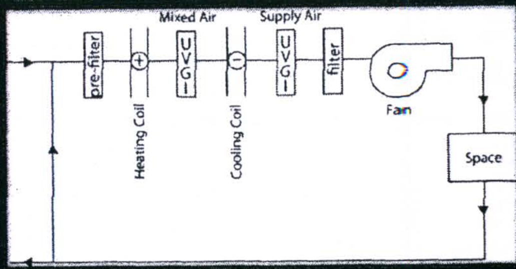
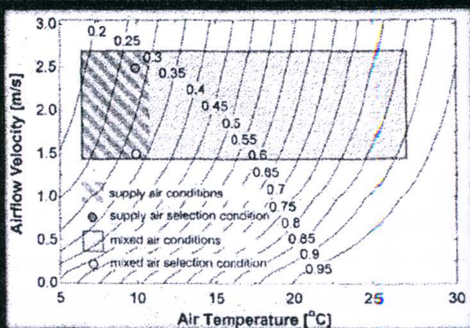
Study Cases

- 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)



System Parameters

- Size for worst-case 85% inactivation of *S. aureus*
  - k = 0.0035 $cm^2/\mu J$; Required dose: 542 $\mu J/cm^2$
  - d = 1 µm (η_f = 15% for MERV 6, 85% for MERV 12)
  - Constant source during business hours (0900 - 1700)
- Philips TUV PL-L 60W HO lamps in cross flow, modeled per Lau et al. (2009)



Results-UVGI Selection

- Input power required depends on location
- Supply air is colder, causes greater derating of lamp

	Supply Air	Mixed Air
Temperature, °F	50	50
Velocity, fpm	500	300
Exposure time (s)	0.3	0.5
Lamp Output (%)	27.8	32.9
Irradiance (µW/cm²)	6499	3295
Input power (W)	718	364

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: $150/ft² initial cost, $20/ft² per replacement, change every 6 months
  - 1-inch H_2O additional pressure drop
- Electric power
  - $0.10/kWh
- Discount rate
  - 3% real rate

Results-Annual 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/ft^2	4802 0.2	2477 0.1	26,644 1
Cost ($) $/ft^2	480 0.019	248 0.010	2664 0.104

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Results-Annualized Life-Cycle Cost

- Unit costs in $/ft^2
- Does not include IAQ benefit credit

	UVGI in Supply Air	UVGI in Mixed Air	MERV 12 Filtration
Installation	0.024	0.012	0.017
Replacement	0.028	0.014	0.053
Energy	0.017	0.009	0.096
Total	**0.069**	**0.035**	**0.166**

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SUMMARY

Summary

- UVGI is not new and there is a lot of evidence to support its effectiveness.
- As an industry, UVGI is still developing and needs more research, standardization and openness, but that is not a reason to avoid using it today.
- Care needs to be taken when selecting organic materials that will be in line-of-sight of direct/reflected UV energy.
- UVGI can work well with particulate filtration to reduce exposures to airborne microorganisms.

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