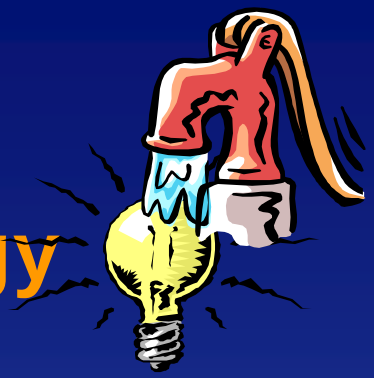
UV Disinfection:
An Age-old Emerging Technology for Safe Water



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DUKE
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SCHOOL OF ENGINEERING

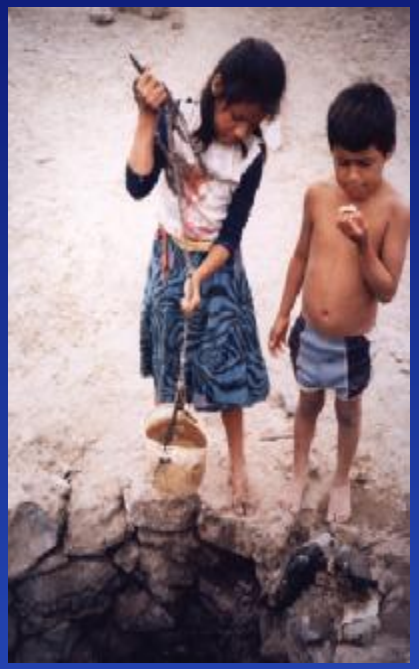
NAE: 2007 Frontiers of Engineering: Safe Water Technologies

Mortality and Morbidity From Unsafe Drinking Water

- Each year:
  - 1.7 – 2.2 million persons die from waterborne diseases
- Each day:
  - 5,000 children die from infectious diarrhea acquired from unsafe drinking water
- Each year:
  - 4 billion episodes of diarrhea are caused by unsafe drinking water

Global Burden of Unsafe Water

- Over 1 billion persons have no access to improved water sources



- Hundreds of millions more drink unsafe water from “improved” sources

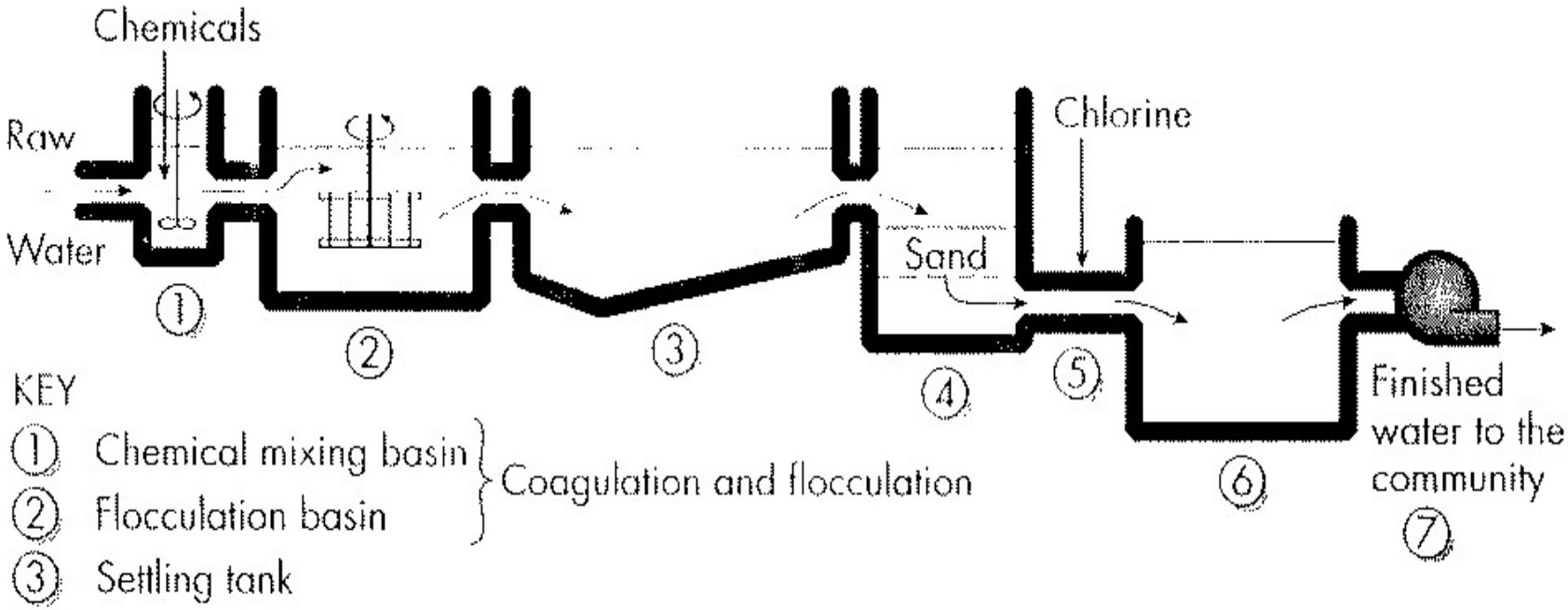
The Issue with Water

- Essential for Life
- A Scarce Resource
  - Compromised quality
- We take it for granted
  - Major issues outside of Industrialized Areas
- $16B spent on bottled water (USA)
- 1B bottles transported per week
- Environmental / Energy / Sustainability

Cost of 1 bottle of Evian would buy >500 gallons of safe tap water

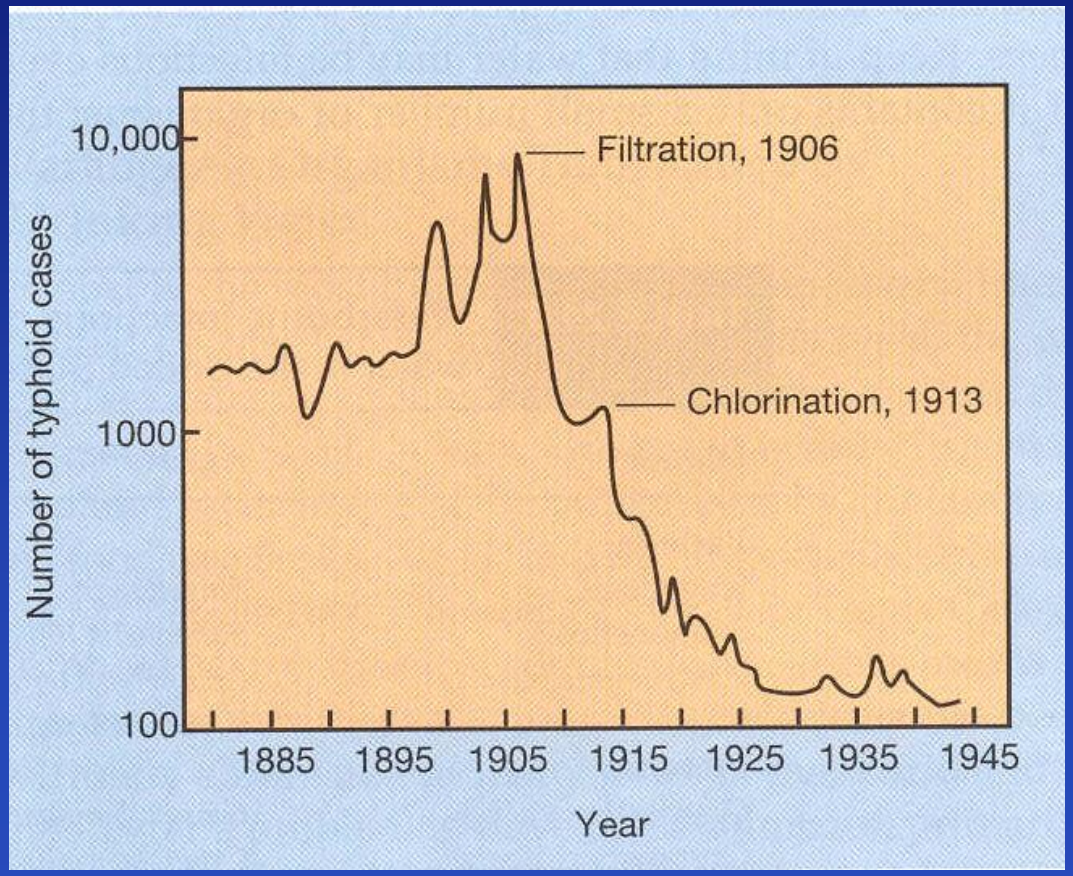
The New Water Cycle in Our Modern World

Water Treatment (20th century)



Vesilind, 2001

The Dawn of Modern Water Treatment



Typhoid Fever in Philadelphia

- Disease incidence in United States grows in populated areas
- Traced to water
- Filtration using sand
- Chemical chlorine for disease control

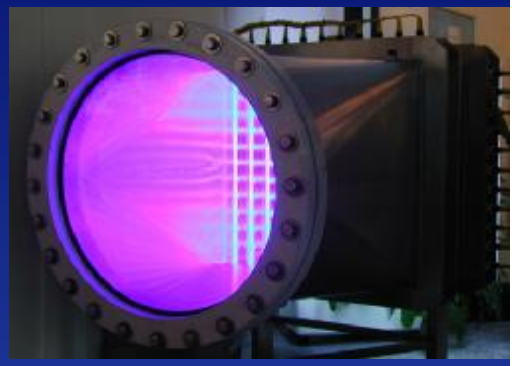
- Same Processes Used Today: 100 years old…

Chlorine Disinfection: The Ugly

- 1970's: Chlorinated water recognized as containing carcinogenic disinfection byproducts (DBPs)
- 1980's: EPA regulations minimizing levels of DBPs
- 1990's: Chlorine realized as ineffective against protozoan pathogens (e.g. Cryptosporidium, Giardia)
- 2000's: EPA regulations requiring disinfection of Cryptosporidium, lower thresholds for DBPs

Also: Bad taste, Poor public perception

Why UV? Why Now?



- Disinfection
  - Effective physical disinfectant process
  - VERY effective against Cryptosporidium
  - NO byproduct formation (no halogens)
  - Ideal for wastewater: discharge to natural system
  - No residual chemical (good and bad)
  - Works at the speed of light
  - As old as the Sun

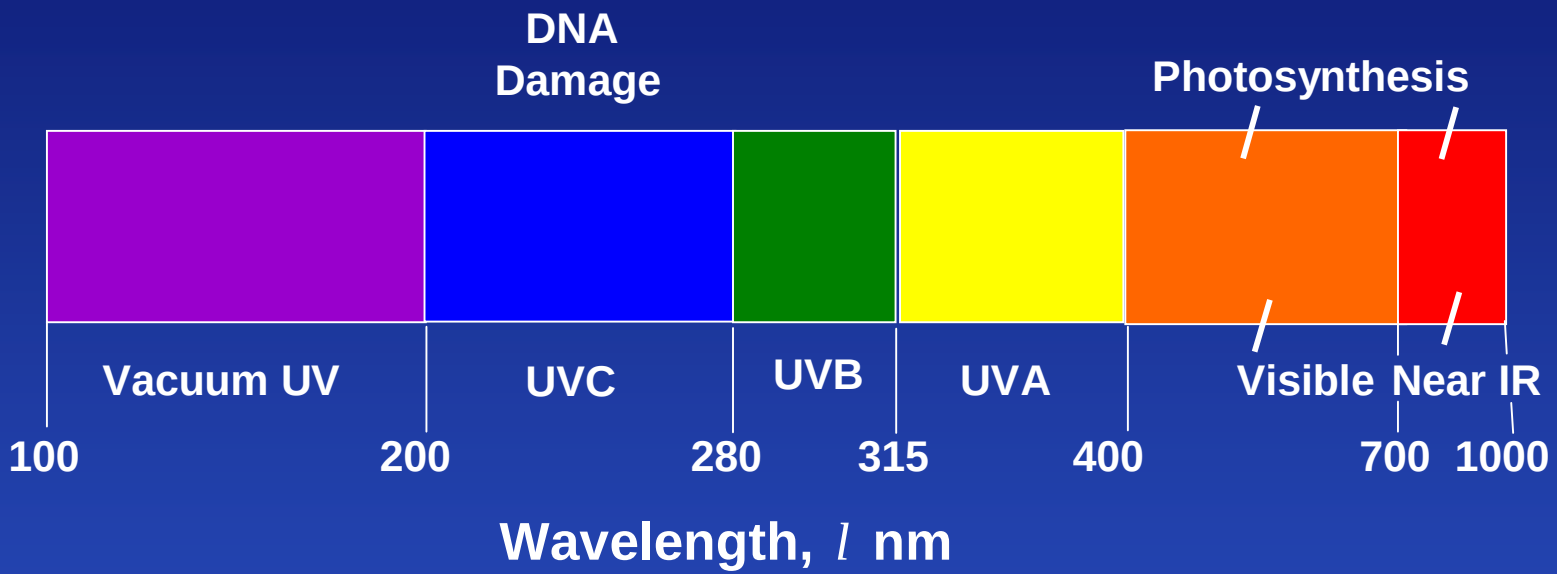
- Oxidation of chemical contaminants
  - Photolysis and oxidation of emerging pollutants

Principles of UV Photobiology

- Absorption of Light
  - Only light that is absorbed can produce a photobiological effect
  - Need to know the absorbance spectrum of the target

- Energy of Light
  - Enough energy needs to be transmitted to cause a lasting photobiological effect
  - Need to know the amount of energy (UV “dose”) delivered (Measured as mJ/cm^2)

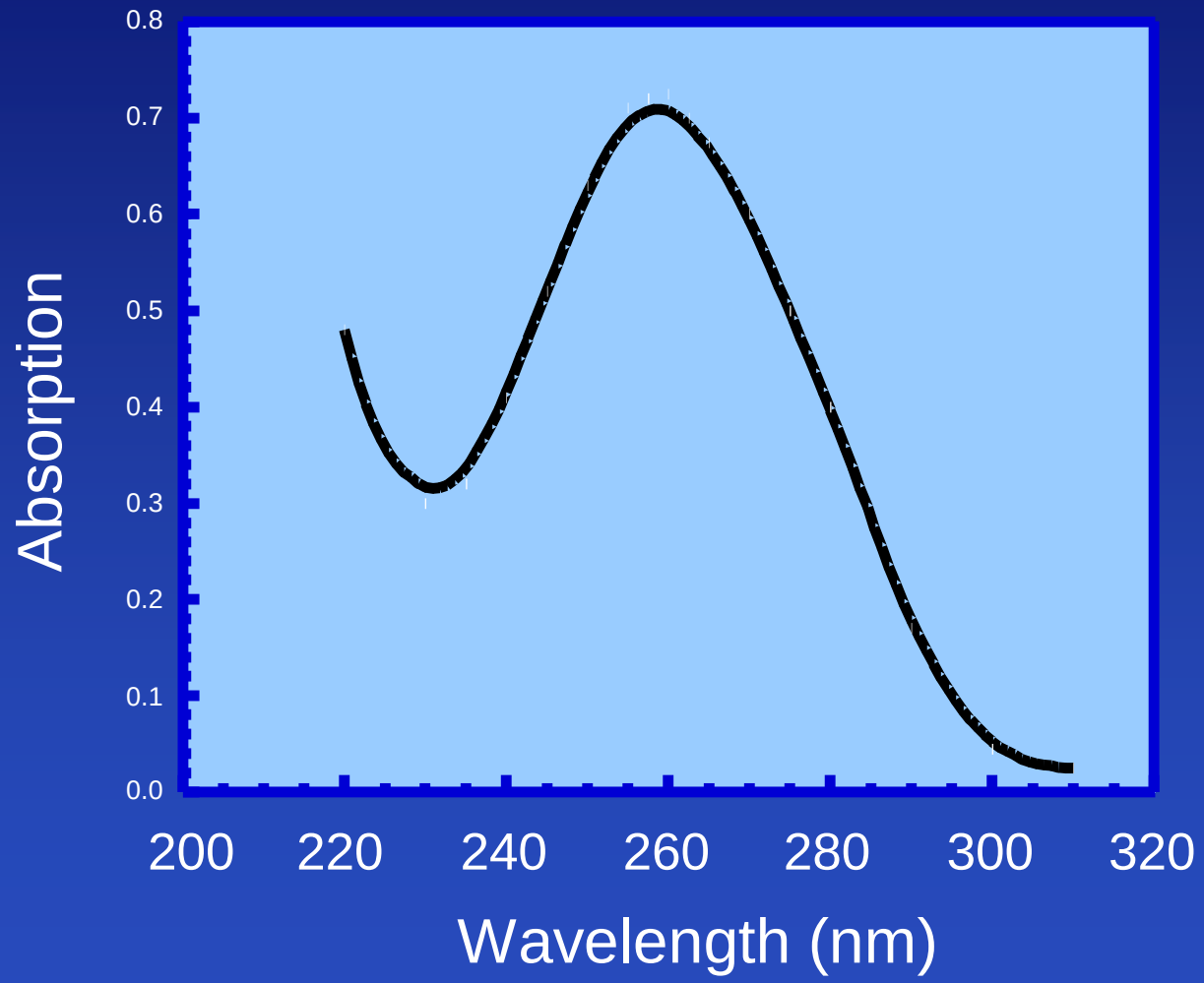
Electromagnetic Spectrum



High Energy

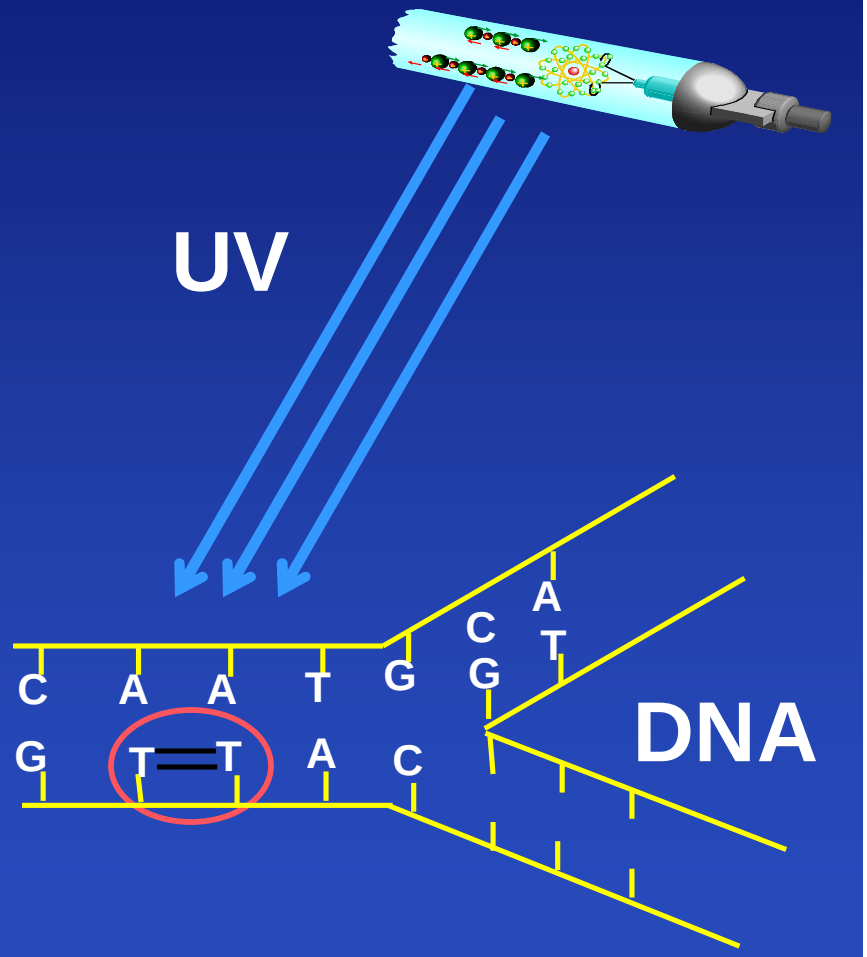
Low Energy

Absorbance Spectrum of DNA



UV Mechanism of Action - Overview

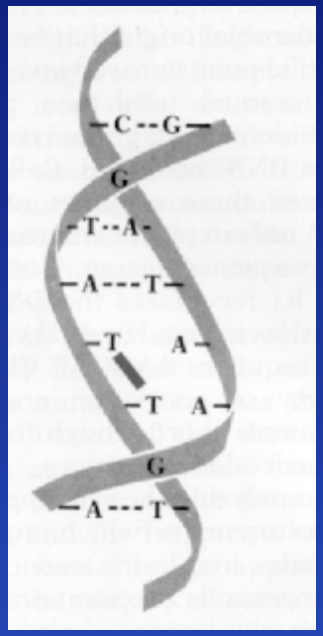
- Physical Process
- Light Energy Absorbed by DNA
- Dimer Formation
- Inhibits Replication
- Organism that Cannot Replicate, Cannot Infect
- Still Metabolically Active

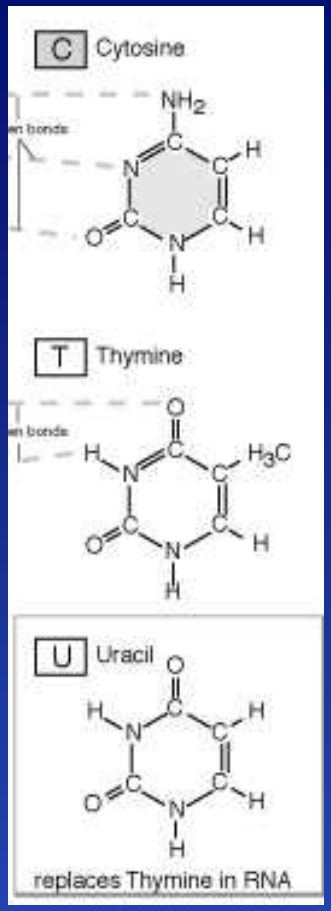


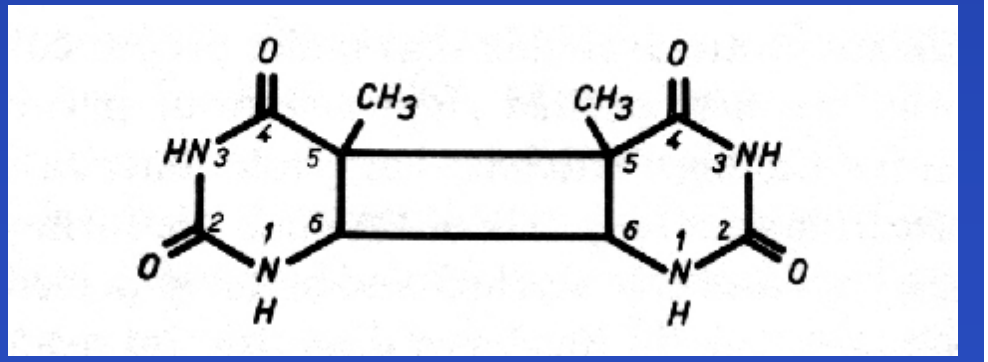
Pyrimidine Dimers

- Thymine dimers most prevalent
- Interference with replication and transcription
- Inactivation of bacteria, viruses
- Lethal for a cell

- ~90% of UV damage in bacteria is dimer based

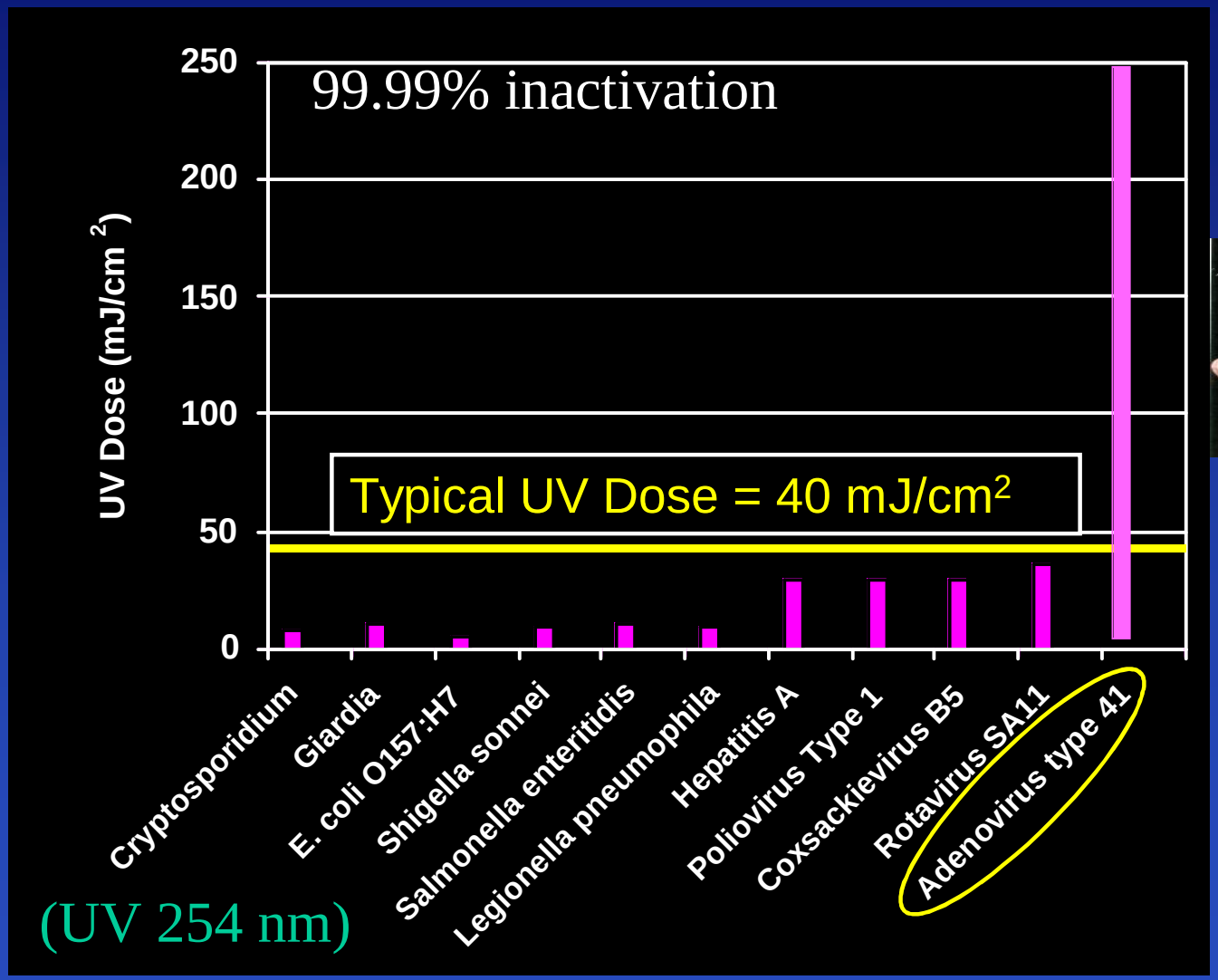


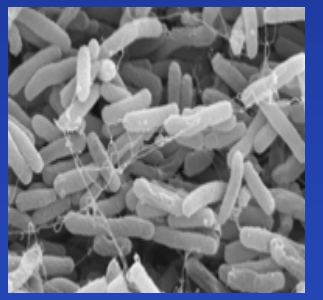


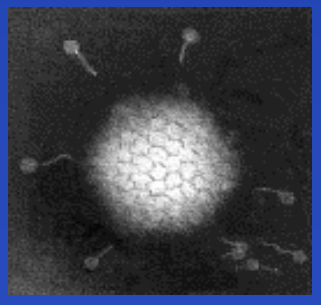


Kittler and Lober, 1976

Disinfection Efficacy



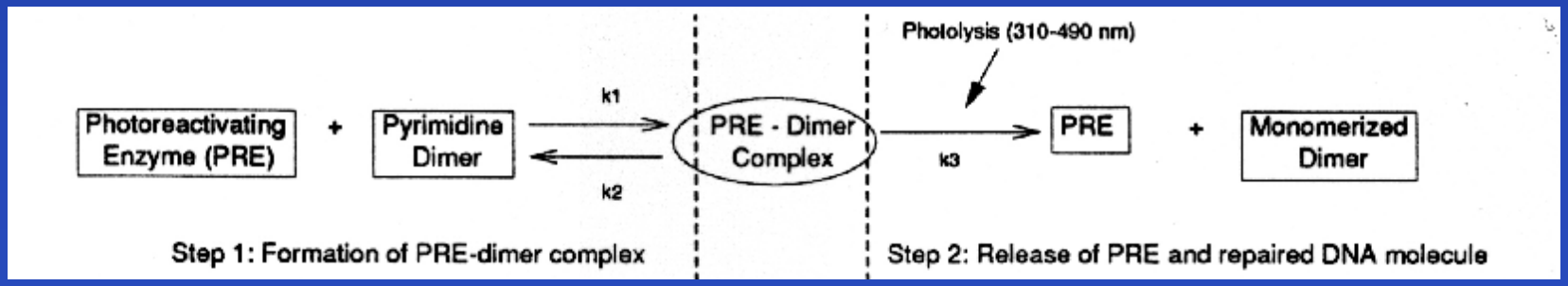




Durance, 2005

But…….DNA Repair

- UV inactivation not immediately lethal
- Potential to repair damage and restore infectivity
- May occur due to photo-repair or dark-repair
- Not all microbes can repair UV damage



Linden and Darby, 1993

UV: The Next Generation

Investigating Polychromatic Advantages

Comparison of disinfection efficiency for

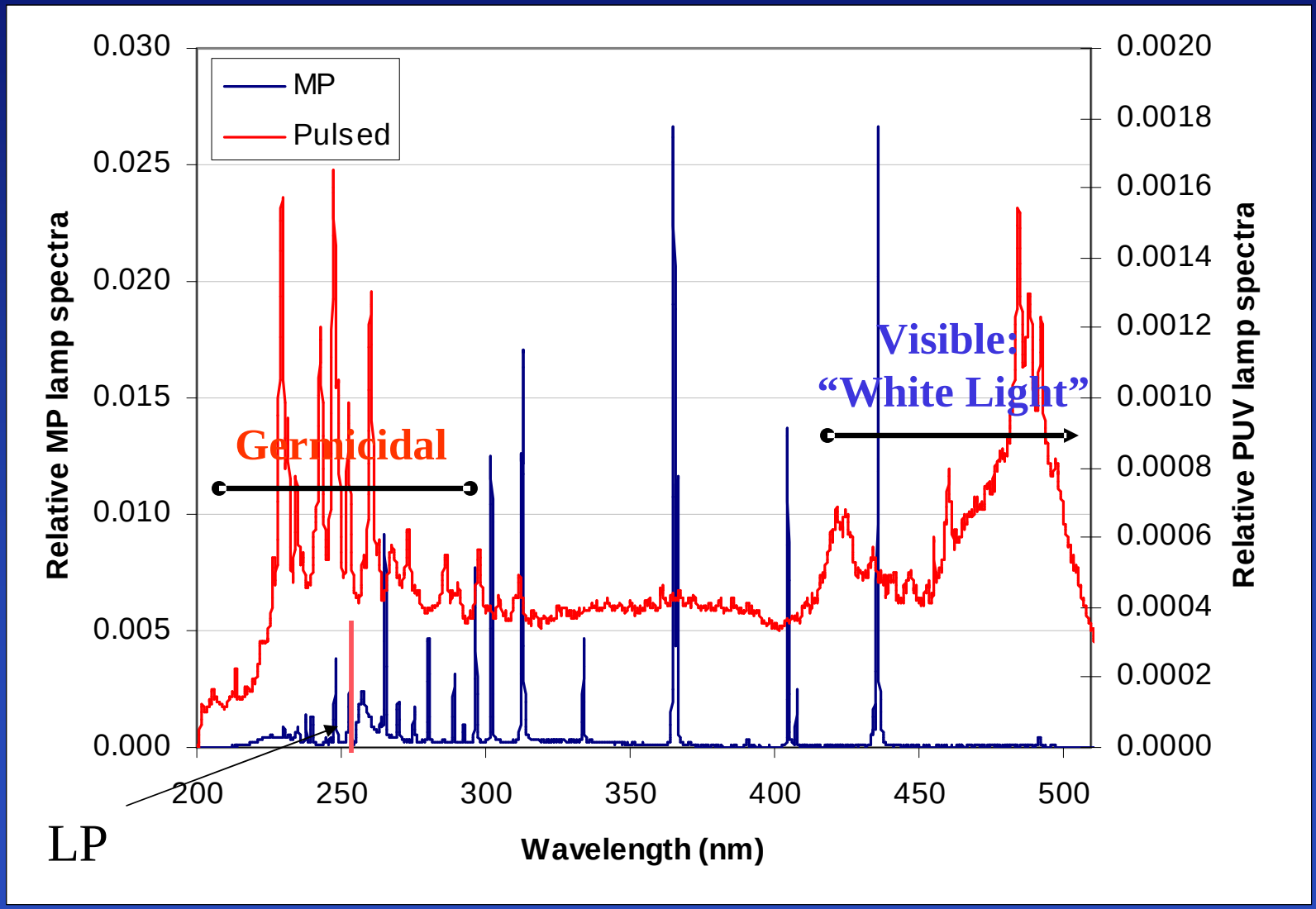
low pressure (LP) mercury vapor lamps,

medium pressure (MP) mercury vapor lamps,

and

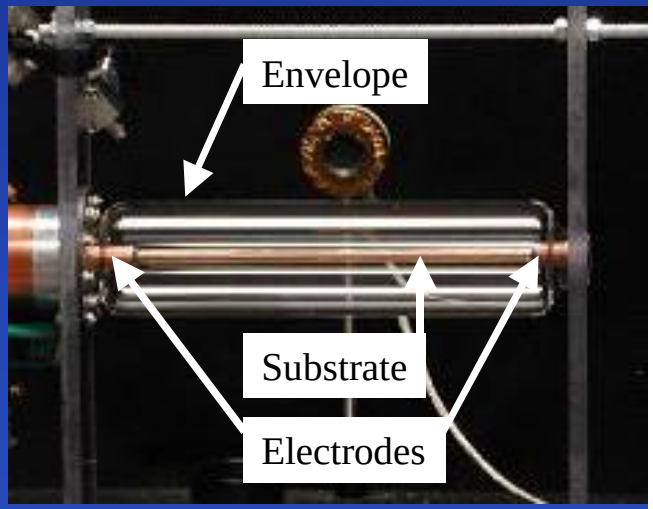
pulsed UV (PUV) non-Hg lamp

Lamp Emission Spectra

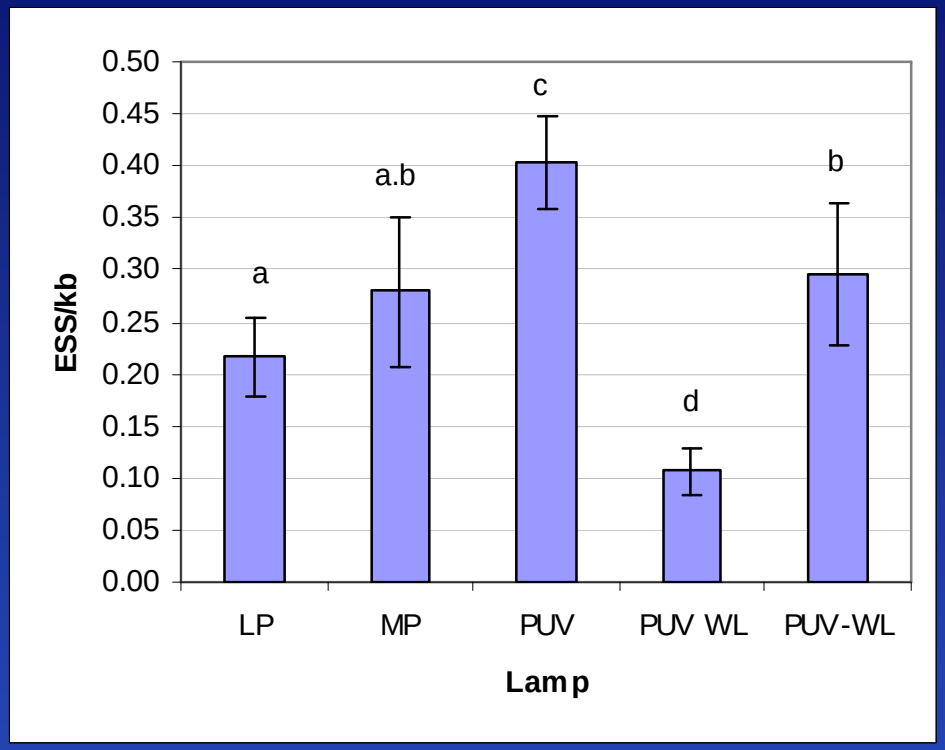


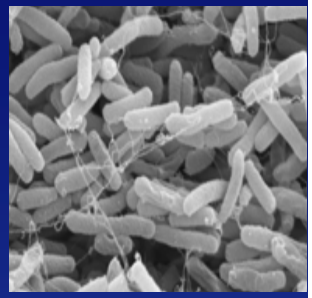
Pulsed UV (PUV)

- Polychromatic (>200 nm)
- Xe lamp (not Hg-based)
- High intensity *pulses* of radiation
  - 10,000x higher than LP and MP
- High temperatures (10 000^{o}K)
  - lamp must be cooled
- Applications in packaging/food disinfection
  - higher penetration depth than continuous wave-UV



E. coli – thymine dimers



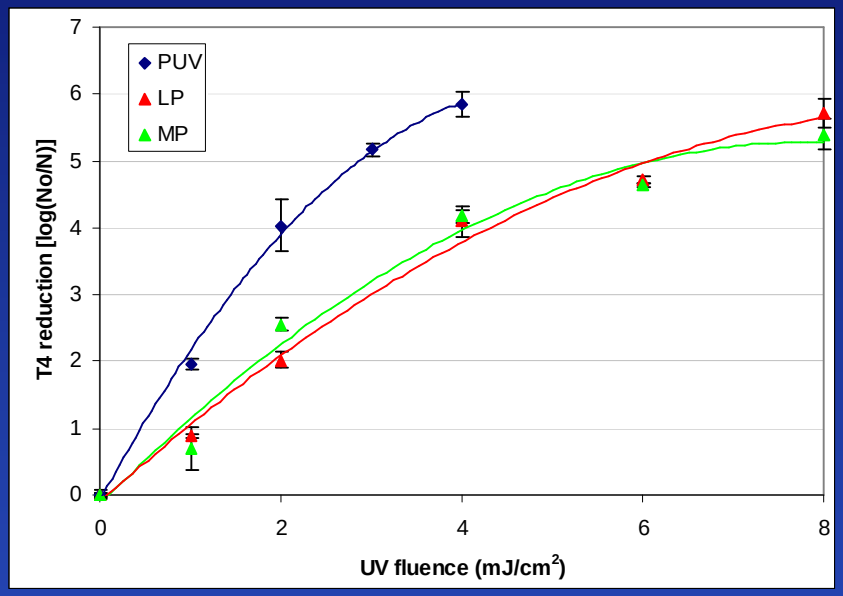


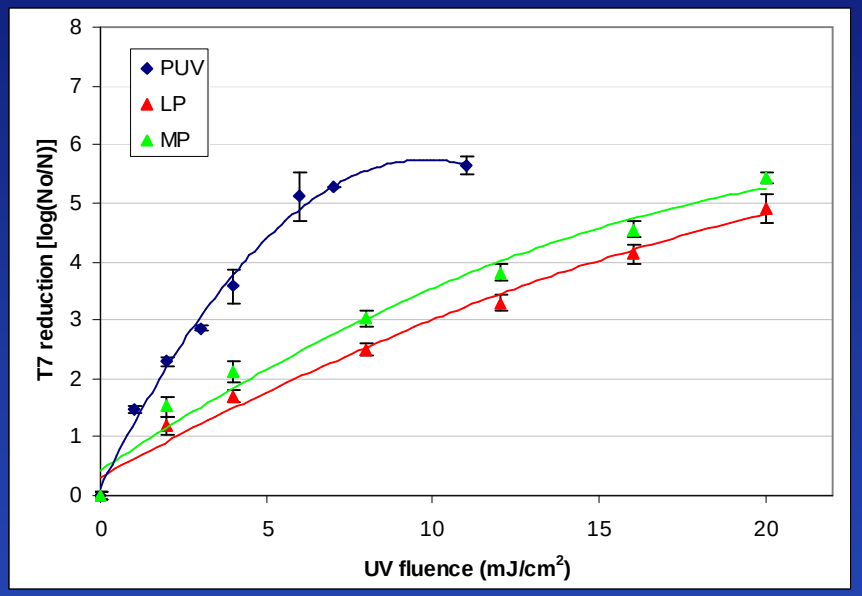
UV Dose = 3 mJ/cm^2

WL = White Light

- No significant difference in # of thymine dimers/kb created by UV-C light portion using LP, MP and PUV
- Some thymine dimers created by PUV light >290 nm

T4 and T7 Phage Inactivation with LP, MP and PUV





The PUV inactivation of T4 and T7 was significantly higher than inactivation using LP, MP UV Sources

Enhancement due to damage from wavelengths >295 nm

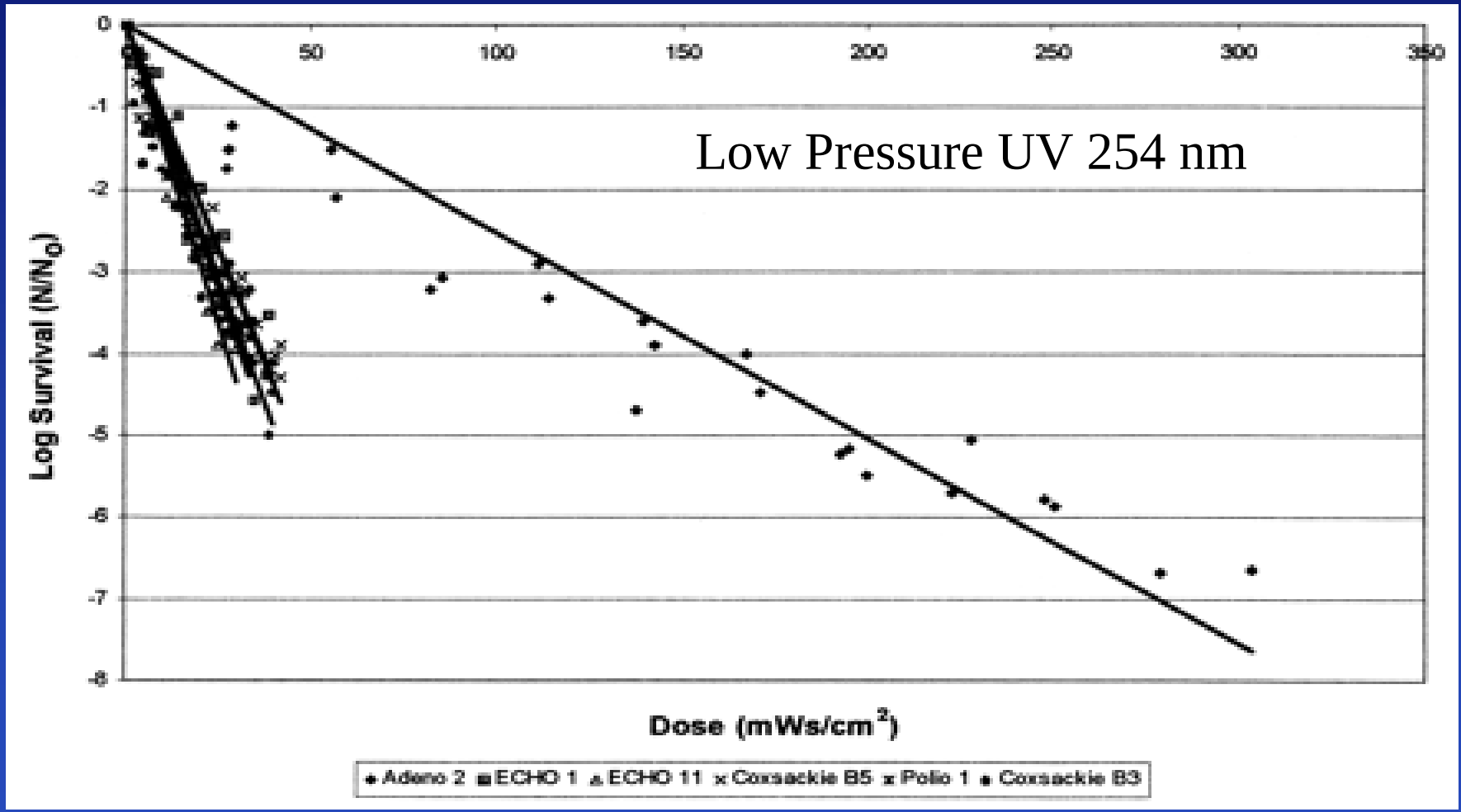
Only High intensity PUV - not seen with MP UV >295 nm

The Adenovirus Challenge

- Cause respiratory and enteric illness
- 52 human serotypes in six subgroups
  - Group C: Ad2 and Ad5
  - Group F: Ad40 and Ad41
- Impact on regulations!
  - EPA Candidate Contaminant List (CCL)
  - Long-Term 2 Enhanced Surface Water Treatment Rule
  - Groundwater Rule

UV disinfection requirements for ALL viruses is governed by adenovirus

UV Treatment of Viruses

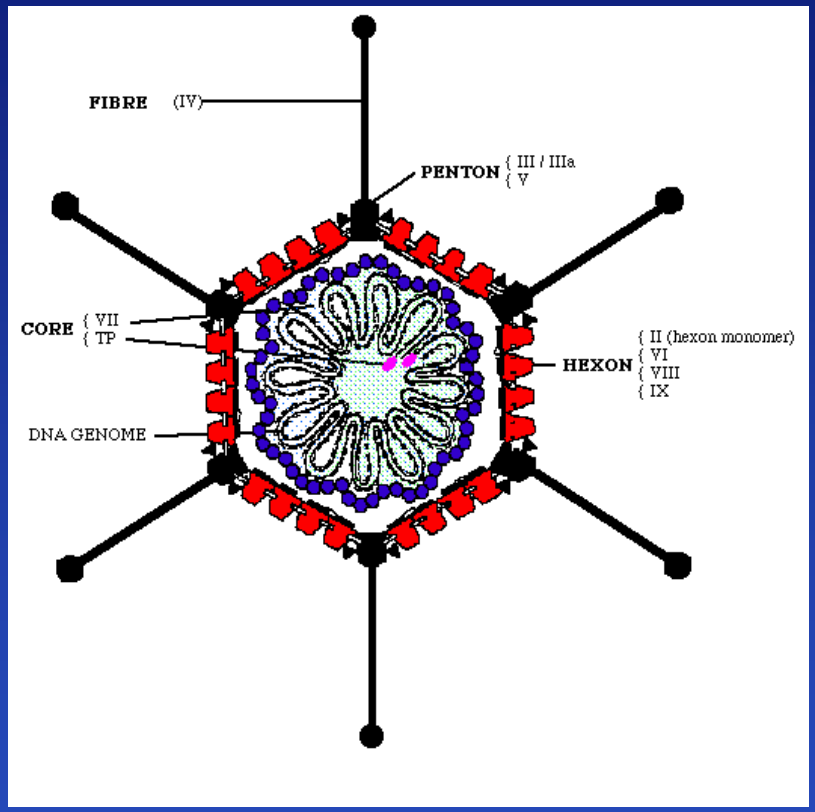


Gerba et al., 2002

Why is Adeno so UV Resistant?

- Studies only performed with LP UV
- Specific DNA damage from UV 254 nm
  - Thymine dimer
- Hypotheses
  - Significant dimer damage occurs
  - Damage is repaired in host cell
  - Infectivity is restored/DNA replicated
    - Adeno is a dsDNA virus (same as host)
  - Higher UV doses required to form enough DNA damage to overcome repair

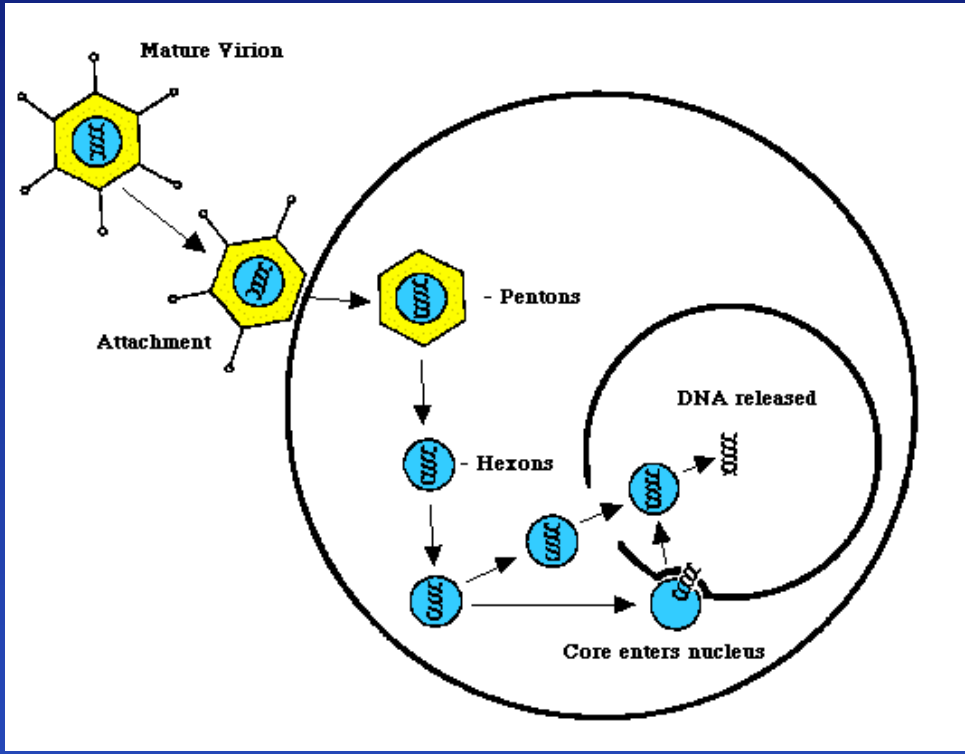
Structure of Adenovirus



- Icosahedral
- Nonenveloped
- 70 nm -100 nm
- dsDNA genome--!!!
  - Same as host cells

http://www.tulane.edu/~dmsander/WWW/335/Adenoviruses.html

Infectious Cycle of Adenovirus



www.tulane.edu/~dmsander/WWW/335/Adenoviruses.html

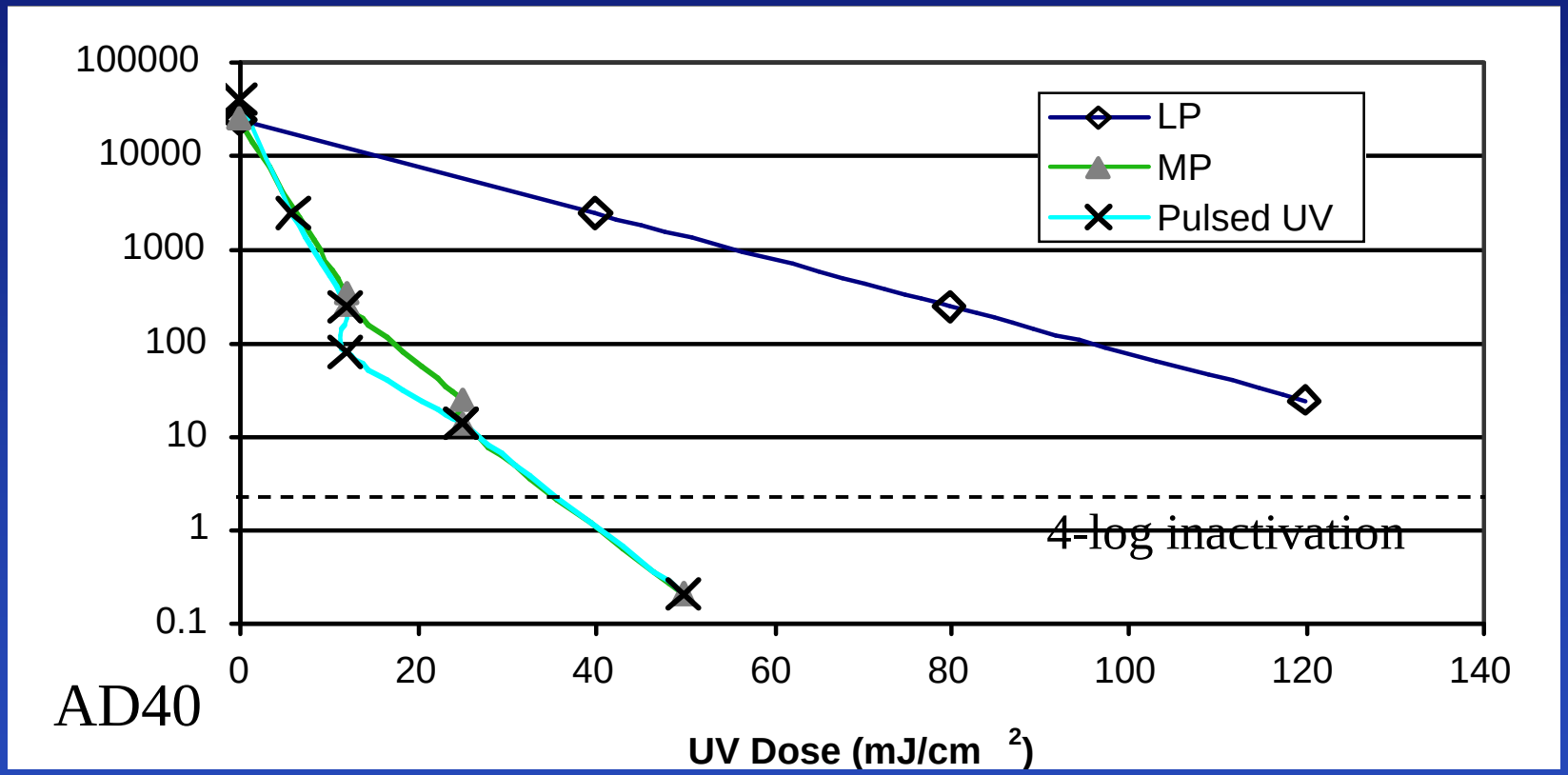
- Attachment
- Endosome lysis
- Travel to nucleus
- Transcription of viral DNA in host nucleus
- Viral PROTEINS essential at all steps

With UV 254 nm, Proteins still intact, virus can attach to host

UV Treatment of Adenovirus

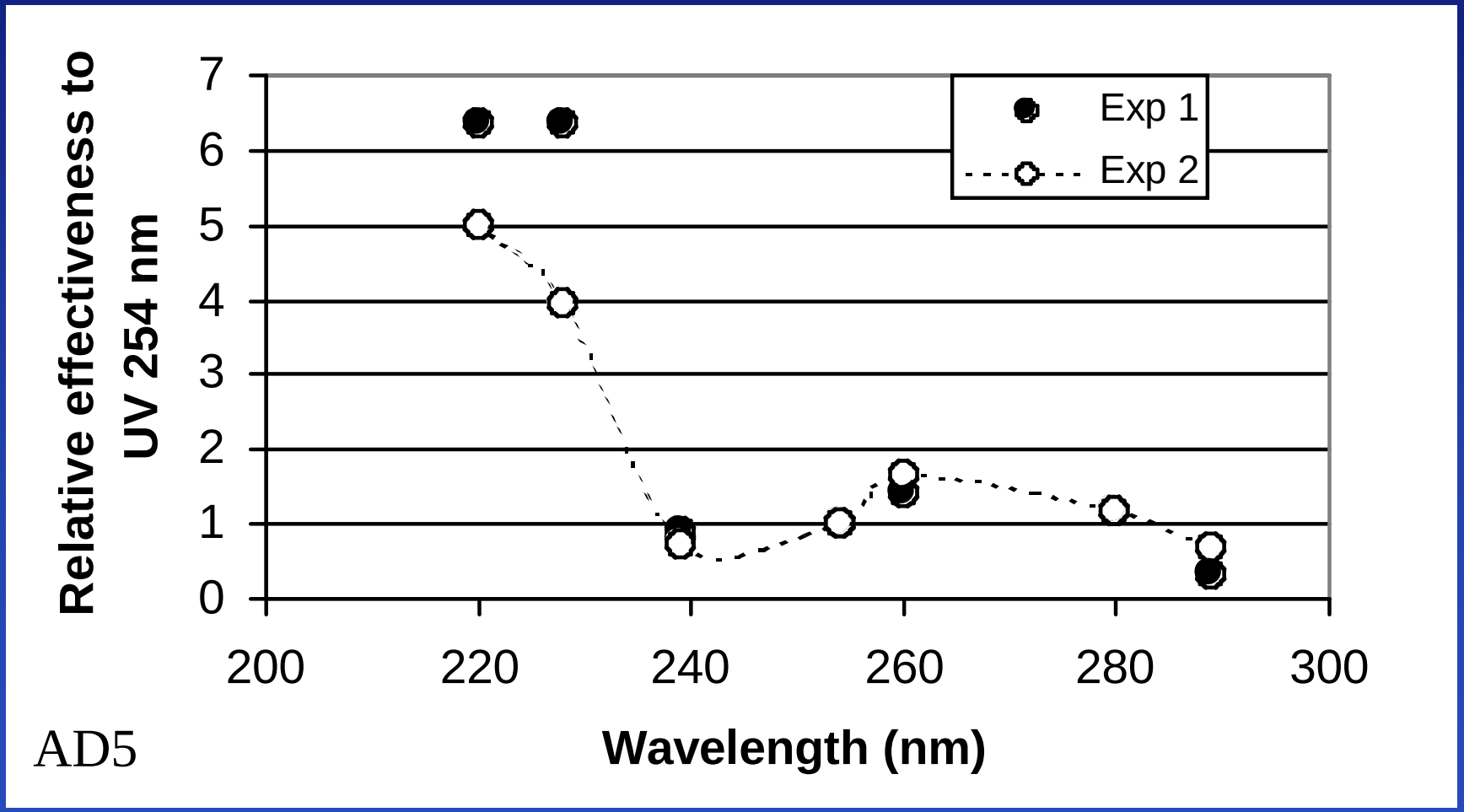
- Low pressure UV
  - Damages only DNA
- Cell culture infectivity assays
  - Potential for repair using host cell
- 120-200 mJ/cm^2 for 4-log inactivation
  - 30-40 mJ/cm^2 for other viruses

UV Disinfection Technologies



Linden and Thurston, 2006

Disinfection at <240 nm: Germicidal Action Spectra for Adenovirus



(Linden et al., 2005)

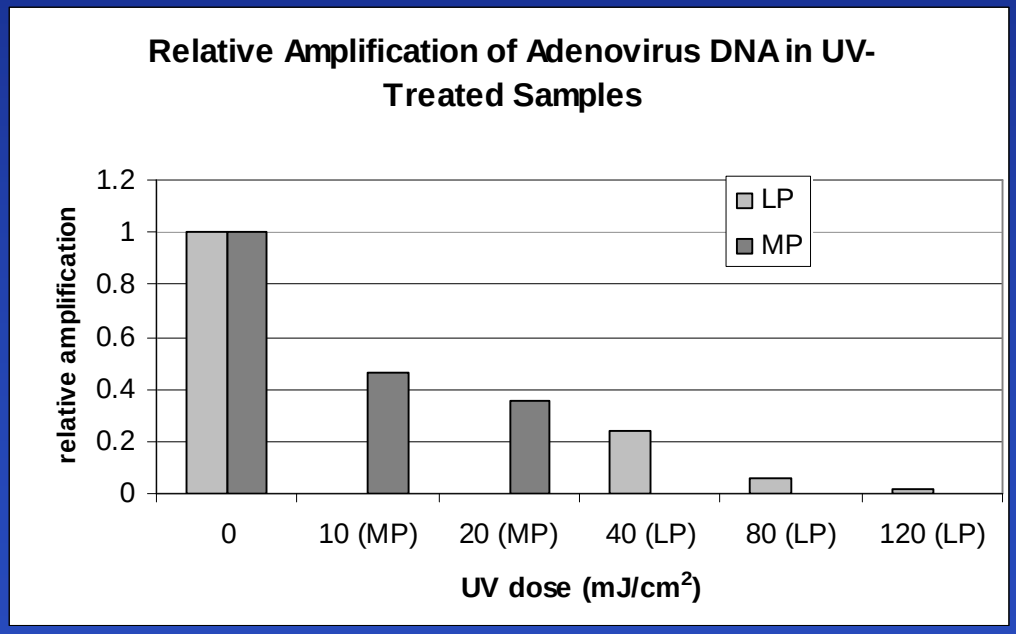
Hypotheses Being Tested

- Hypotheses
  - LP, MP and Pulsed UV will cause similar DNA damage
  - MP and Pulsed UV will cause greater protein damage
    - Will correlate with greater loss of capsid integrity and decreased infectivity
- Approach
  - Apply molecular techniques for direct assessment of damage to proteins, capsid structure, and DNA
  - Use newer UV technologies to induce damage to proteins
  - Compare to standard cell culture assays
  - Perform animal infectivity evaluations on murine adeno

DNA Damage

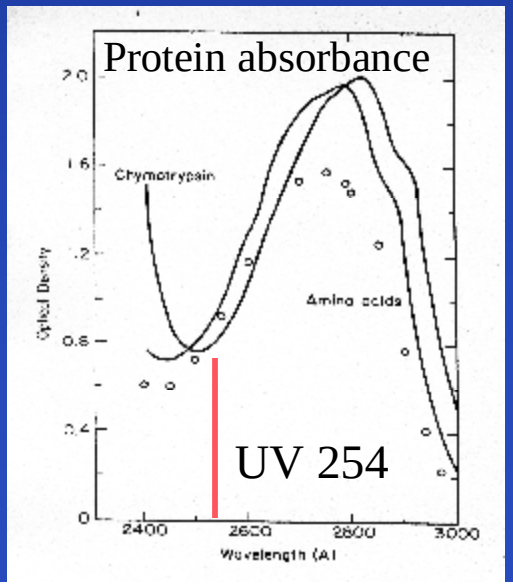
- Monochromatic 254 nm and polychromatic UV induce similar levels of DNA damage

Long Quantitative Polymerase Chain Reaction



-Polymerase progression inhibited by DNA damage
-More damage = less amplification

Then why are polychromatic UV sources so much more effective?



Future of UV Treatment??

- Engineering decisions on type of UV
  - LP vs MP, small vs large systems, SW vs GW
- Pulsed UV almost ready
  - Lamp lifetimes, Hg vs non-Hg
- New UV sources:
  - UV-LEDs (sustainable applications, LDCs)
  - Excimer UV
  - Solar Disinfection (SODIS) in LDCs
- Bringing UV technology to lesser developed countries

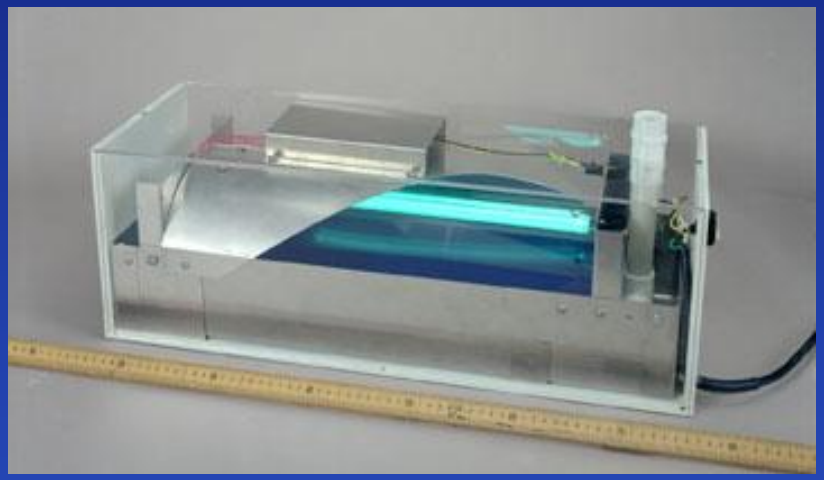
GTA GREEN TECHNOLOGY ASSOCIATES, LLC

Bring Your Own Water (BYOW) Treatment System

- Solar Powered UV lamp
- Sand filter
- Affordable, Simple
- Construct from local materials
- 15-40 Watt Bulb

Colorado-Boulder Engineers Without Borders

The LBL UV System

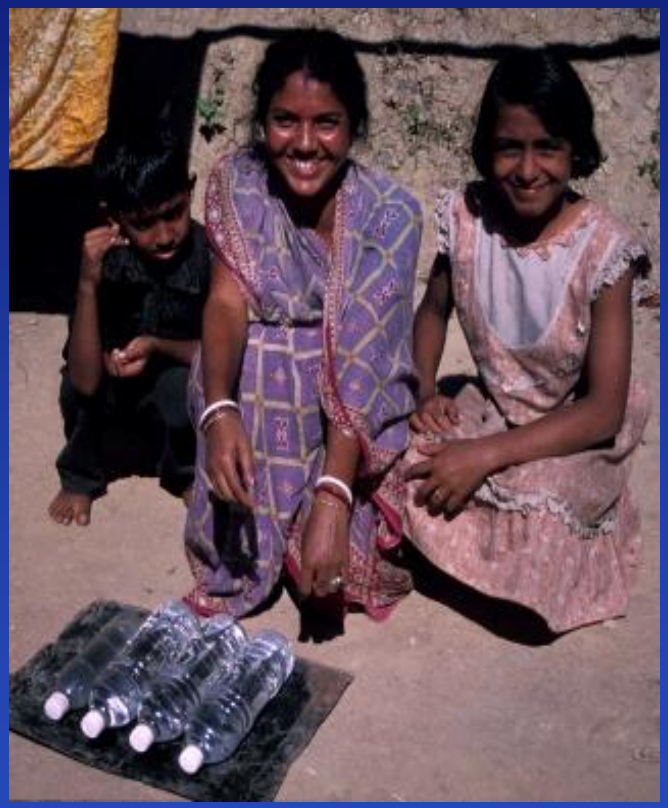


UV Waterworks

- Typical LP UV lamp
- Affordable, Simple
- Needs electricity/ solar powered
- Construct from local materials
- Lamp out of water
- Reflector used
- ~$300 cost

Safe Rural Water Supply

+



Daniele Lantagne, CDC

UV: Cross-cutting discipline

- UV disinfection integrates fundamentals
  - Photochemistry
  - Photobiology
  - Molecular Biology
  - Physics
  - Engineering Design

- All integrated to provide public health protection
  - Minimizing unwanted byproducts
  - Optimizing pathogen control
  - Providing easy tool to serve all types of communities

Collaborators and Funding

- Duke University
  - Anne Eischeid, Doctoral student
  - Dr. Zuzana Bohrerova, Post-doctoral researcher
- USDA-ARS
  - Jeanette Thurston
- US EPA National Risk Management Research Lab
  - Dr. Chris Impellitteri
- Industry
  - Bob Lantis: LightStream Technologies, Herndon, VA
  - Raymond Schaefer: Phoenix Science and Technology, MA
  - Mark Bent, Sunnight Solar, Houston, TX

Funded by
US EPA
Water Utilities
WateReuse
Foundation

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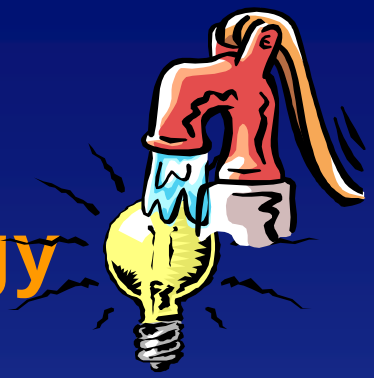

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