CIE-USNC 2020 Meeting - Technical Presentation

Evolution of UV-C Safety Guidelines and Standards

In 1971 the American Conference of Governmental Industrial Hygienists (ACGIH) proposed the first broad-band occupational exposure limits for ultraviolet radiation. After public review and comment, a wavelength-dependent limit covering the entire ultraviolet spectrum with a spectral weighting function S(λ), or "envelope action spectrum" from 200 nm to 315 nm (later extended in 1988 to 400 nm). The International Commission on Non-Ionizing Radiation Protection (ICNIRP) later adopted similar limits in 2004. These guidelines for limiting exposure to UV radiation were later employed as the basis for emission limits for risk assessment of lamp products in photobiological safety standards for lamps. The first photobiological safety standards for lamps was issued in the early 1990s by the Illuminating in Engineering Society and those standards in turn were the basis of CIE Standard S009 for the Photobiological Safety of Lamps and Lamps Systems. There have been little changes in any of these exposure limits or lamp safety standards over the past two decades but because of the COVID-19 pandemic there has been great interest in new interpretations and potential revisions of the current UV-C exposure limits as applied to UV germicidal region of the spectrum; and these will be explored.

David Sliney, Ph.D.

David H. Sliney holds a Ph.D. in biophysics and medical physics from the University of London (Institute of Ophthalmology), an M.S. in physics and radiological health from Emory University (Atlanta, GA, USA) and a B.S. in physics in from Virginia Polytechnic Institute (Blacksburg, VA, USA). He worked for the US Army Public Health Center for 42 years, serving as Program Manager, Laser/Optical Radiation Program, which he held until his retirement in 2007. He currently serves as an independent consultant. He has been active in the establishment of health and safety standards for protection of the eye and skin from lasers, ultraviolet and high-intensity optical sources. His studies in vision, thermal and photochemical effects upon ocular tissues have aided the development of laser applications in medicine and surgery. He is perhaps best known for two well-cited books: with Prof. Myron Wolbarsht , "Safety with Lasers and Other Optical Sources," and with Prof. Stephen Trokel, "Medical Lasers and Their Safe Use." Dr. Sliney has long been active in the CIE and served as the Director of Division 6 for two terms from 1991 to 1999 and as a vice-president. He has published well over 200 peer-reviewed scientific papers—many relate to the development and optimization of laser/optical applications in eye surgery and ophthalmic diagnostics. He has served on the editorial board of a number of scientific journals, including Photochemistry and Photobiology, Health Physics, Journal of Laser Application, Laser Applications in Medicine and Surgery, Lasers and Light in Ophthalmology and Annals of Ophthalmology and Glaucoma. He has served as member, advisor and chairman of numerous committees active in the establishment of optical safety standards (ANSI, ISO, ACGIH, IEC, WHO, NCRP, and ICNIRP). He was a Fulbright Scholar to Yugoslavia in 1977 and received both the Wilkening Award and Schawlow Award from the Laser Institute of America and the Award for Distinguished Scientific Achievements from the Health Physics Society in 2009. Dr. Sliney was the chair of a task group on “Adjustment of guidelines for exposure of the eye to optical radiation from ocular instruments” under the International Commission on Non-Ionizing Radiation Protection (ICNIRP) during 1996-2005. He has associate faculty appointments at Drexel Institute of Technology, Philadelphia, and the Johns Hopkins School of Public Health, Baltimore.

US National Committee of the CIE

EVOLUTION OF UV-C SAFETY GUIDELINES AND STANDARDS

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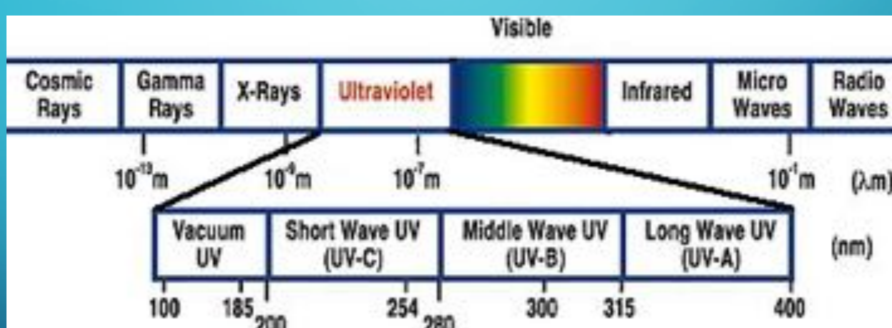
CIE-USNC – 2020 Annual Meeting

THE ULTRAVIOLET AND VISIBLE SPECTRUM ARE OF PRIMARY INTEREST IN PHOTOBIOLOGY…



*…because the **photon energy** is sufficient to interact with biologically significant molecules.*

DAVID SLINEY—IESNA-2019

PHOTOBIOLOGICAL SPECTRAL BANDS

- In the early 1930′s, the CIE Committee on Photobiology created the concept of the CIE photobiological spectral bands and named the bands. These remain as international standards for ***short-hand notation***:

- **UV-A 315 nm to 400 nm ("near UV radiation" or "black light")**
- **UV-B 280 nm to 315 nm ("actinic radiation")**
- **UV-C 100 nm to 280 nm (Germicidal)**

- **Visible 360-380 nm to 780 nm (overlap intended)***

- IR-A 760-780 nm to 1400 nm (0.78 µm to 3.0 µm)
- IR-B 1400 nm to 3000 nm (1.4 µm to 3.0 µm)
- IR-C 3000 nm to 10^6 nm (3.0 µm to 1 mm)

  - Source: CIE Publication 134/1 – Standardization of the Terms UVA1, UVA2 & UVB

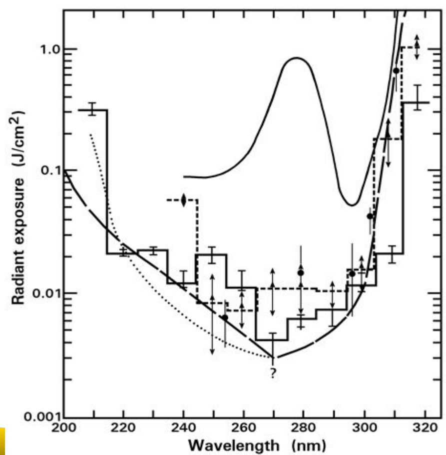
US National Committee of the CIE

BACKGROUND: THE ENVELOPE UV EXPOSURE GUIDELINE

- 1971 – The American Conference of Governmental Industrial Hygienists (ACGIH) proposed the first broad-band occupational exposure limits for ultraviolet radiation
  - a spectral weighting function S(λ), or "envelope action spectrum" from 200 nm to 315 nm
  - S(λ) was extended in 1988 to 400 nm, but still 3 mJ/cm^2 effective radiant exposure
- 1985 - The International Non-Ionizing Radiation Committee (INIRC) of IRPA recommends the same 30 J/m^2, S(λ) limit.
- 1993 – IESNA RP27-1 Photobiological Safety of Lamps & Lamp Systems – the same
- 2003 - The International Commission on Non-Ionizing Radiation Protection (ICNIRP) later adopted similar limits but with more conservative UV-A dose

Spectral Bandwidth Matters –
the UV Hazard Action Spectrum S(λ)

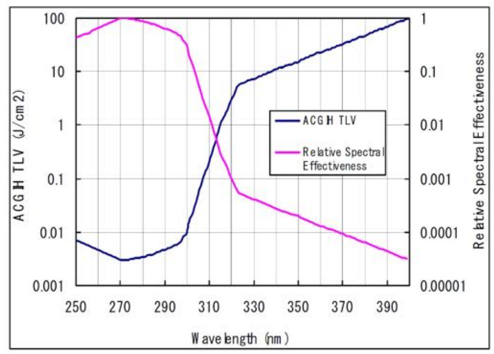
Envelope UV Exposure Limit ACGIH 1972 Weighting Function



Current ACGIH/ICNIRP S(λ) UV Hazard Spectral Function

Absolute action spectrum –

Normalized action spectrum –

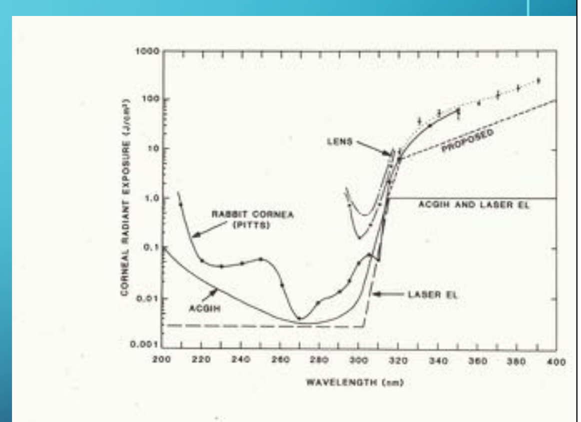


Based upon envelope action spectrum of photokeratitis and min. erythema; Peak wavelength at 270 nm

Target molecule--presumed to be DNA

ACGIH/INIRC EXPOSURE GUIDELINES AND TLV ~ 1985

- Hazard action spectrum S(λ) applied to spectrally weight UV exposure spectrum to produce an "Effective Irradiance."
- Two criteria:
  - 1. The spectrally weighted "effective" radiant exposure is limited to 3 mJ/cm^2
  - 2. The total (un-weighted) irradiance is limited to 1 J/cm^2 in 1000 s for ACGIH (or work day for ICNIRP)
- *Example*: At 254 nm: Limit of 0.2 μW/cm^2 for 8-hr exposure, or 6 mJ/cm^2 for shorter periods
- Free downloads of guidelines: www.ICNIRP.org

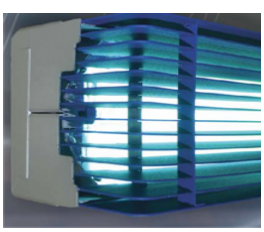


Why is ACGIH Now Considering a Revision of the UV Threshold Limit Value in the UV-C?

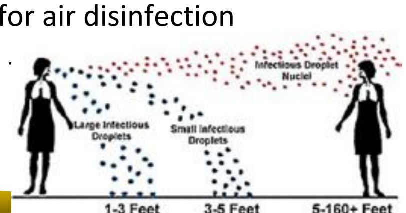
- Limited data for UV bioeffects below 254 nm led to large safety margin. ArF 193-nm laser development gave one endpoint.
- Recent claims (2015-2019) suggested 222 nm much safer
- COVID-19 rapidly revived interest in UV-C for disinfection (UVGI)
  - Traditionally short-wave (UV-C) radiant energy that inactivate many microorganisms (high-energy UV photons): UV Germicidal Irradiation (UVGI)
  - The longer-wavelength photons in UV-B in sunlight are less effective, but still have effectiveness, since summer sunlight is so very intense.
  - Also, UV-A and even short-wavelength (violet) light have been shown to have a direct photobiological effect on some micro-organisms (since 1943), but has a different form of action (Holaender, 1943) and requires O_2 & many thousands or millions more photons than UV-C – not effective for COVID-19

Why is UVGI (or GUV) So Important for Air Disinfection as a Control for SARS-CoV-2?

- Growing evidence of aerosol (airborne) transmission (choir, restaurants, etc.) beyond 3 meters (6.6 ft.)
- Droplet nuclei (1-5 μm) exhaled by pre- symptomatic individuals remain in air (unlike 50-μ – 100 μm coughed droplets) and may be infections for many hours (many unknowns) and UVGI is the only good technique for air disinfection



Louvered (baffled) UVGI Fixture for upper-room air disinfection



Reference:

Nardell, JAMA, June 2020

Meselson, NEJM, 2020

Console air purifiers and in-duct UVGI were shown much less efficient

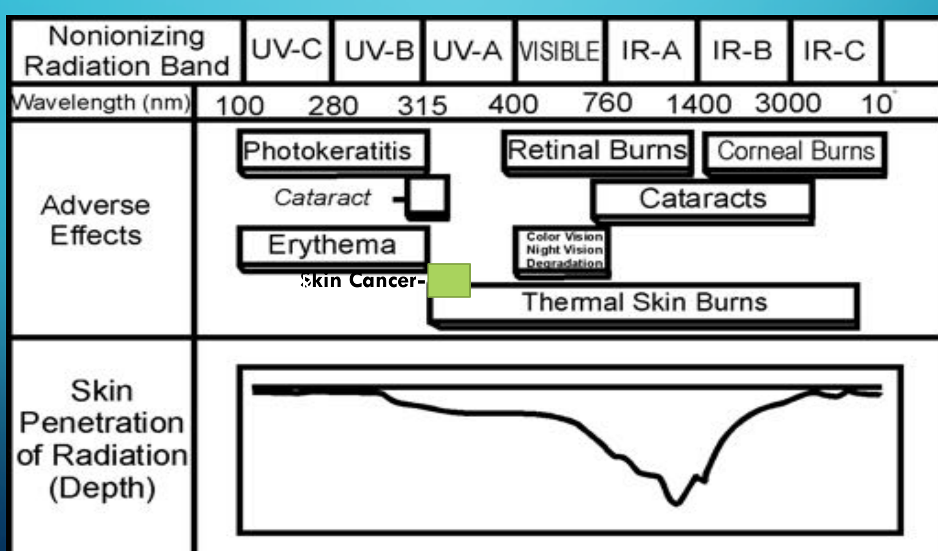
OCCUPATIONAL SAFETY ISSUES

- Ultraviolet Safety is a very important issue!
- Accidental exposure of skin & eyes:
  - Photokeratitis (“welder’s flash,” or “snowblindness” – with symptom of *“sand in the eyes” - Cornea is most sensitive tissue*
  - Erythema – reddening of the skin
    - Can be severe if penetrating UV-B rays (“sunburn”)
    - Mild if UV-C – very superficial absorption
- Delayed Effects
  - Skin Cancer?
    - UV-B in sunlight penetrates to basal (germinative) layer of epidermis and is the recognized cause of most skin cancers
    - UV-C heavily absorbed in superficial epidermis & stratum corneum

- Photokeratoconjunctivitis

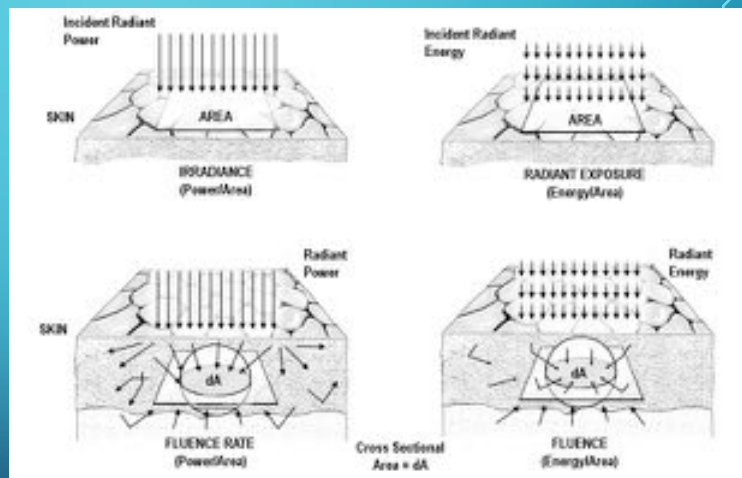
- Erythema (skin reddening)

THE PHOTOBIOLOGICAL EFFECTS
ON HUMANS



DESCRIBING EXPOSURES (CIE)

- *Fluence and fluence rate* include back-scatter and side scatter and multiple passes through a tiny cross section and this is what is important in air and tissue to describe the photo-biological dose and dose rate.
- Howver, we normally just *measure radiant exposure and irradiance*



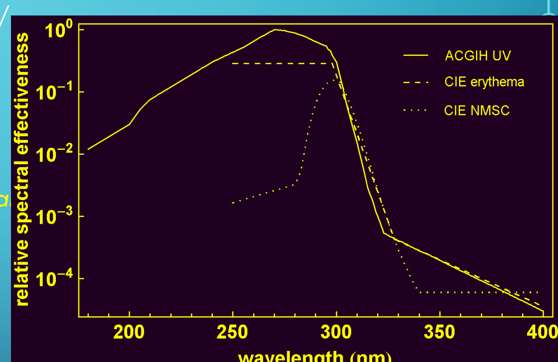
Current guidance – Fluence rate of ~5-50 μW/cm^2 in room air at 254 nm. Remember that UV-C is highly scattering in most media!

WHAT ARE THE SAFETY GUIDELINES FOR HUMAN EXPOSURE IN THE GUV UV – C BAND?

- Action spectrum for safety is the ACGIH/ ICNIRP/ CIE/ISO/IEC action spectrum S(λ)

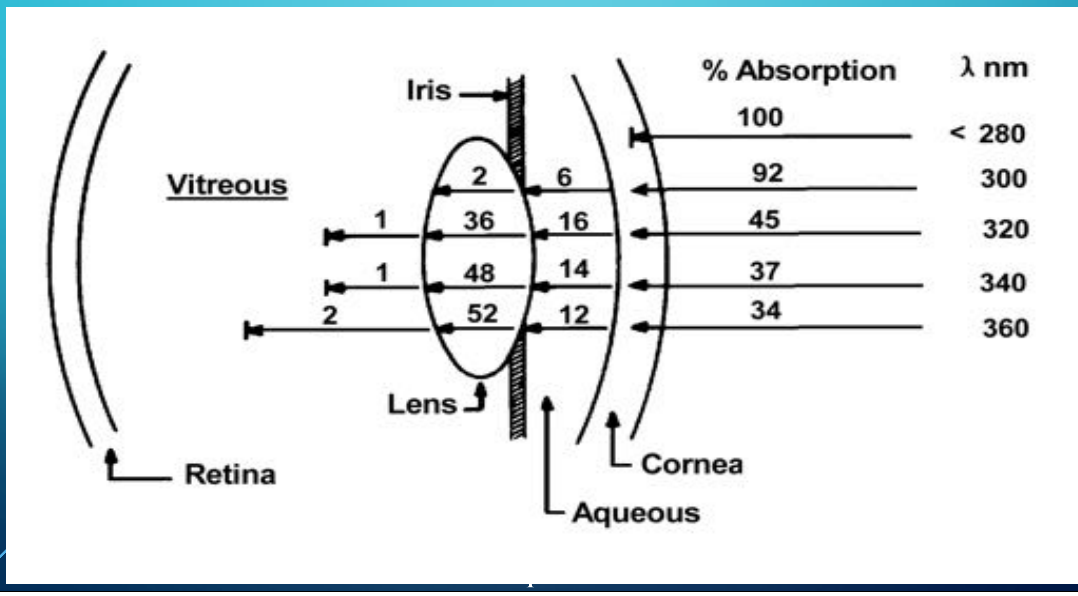
$$E_{eff} = \sum_{180}^{400} E_{\lambda} \bullet S(\lambda) \bullet \Delta\lambda$$

- S(λ)-spectral weighting leads to an *effective radia exposure* of 3.0 mJ/cm^2 (30 J/m^2)
- Limit is daily – including multiple exposures
- Time-weighted average (TWA) over a day
- At 254 nm this is 6 mJ/cm^2 (60 J/m^2)
  - Or, time-averaged irradiance of 0.2 μW/cm^2
- Large safety margin for human skin in UV-C – Should there be two limits? – *For Eye, For Skin?*



- ACGIH UV S(λ) spectral weighting function (action spectrum) is the solid line. S(λ) = 1.0 at 270 nm

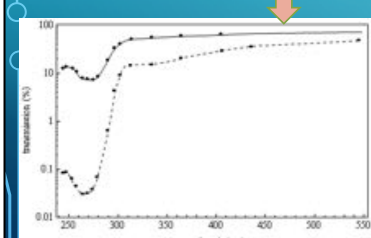
UV SPECTRAL ABSORPTION IN OCULAR TISSUE—SUCCESSIVE FILTRATION – UV-C DOES NOT REACH THE LENS!

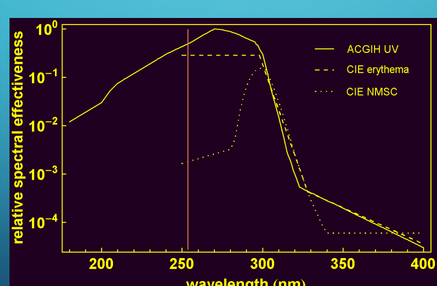


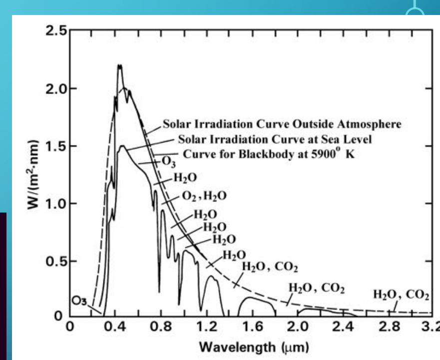
IS THERE A REALISTIC SKIN CANCER RISK?

THE FIRST LAW OF PHOTOBIOLOGY – PHOTONS HAVE TO BE ABSORBED TO PRODUCE AN EFFECT – AND THEY HAVE TO REACH THE TARGET MOLECULES

- TYPICAL CONCERN – If UV-C has highest photon energy why is it not more phototoxic and a more severe skin cancer risk!??
  - UV-B photons are less energetic but they penetrate deeper
- Bruls transmission measurements







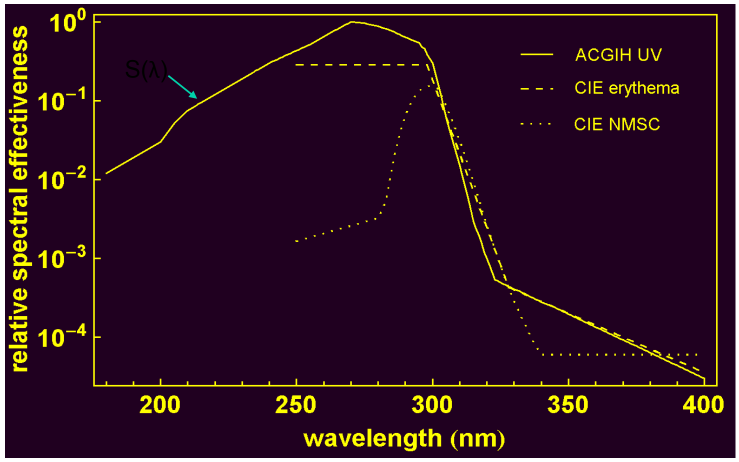
Sunlight spectrum – only trace amounts of UV-B reach ground level and no UV-C at all (Sliney & Wolbarsht, 1980)

See: CIE 187:2010 – UV-C Photocarcinogenic Risks from Germicidal Lamps

Is Germicidal UV 254-nm or 222 nm carcinogenic?

CIE PHOTOCARCINOGENESIS ACTION SPECTRUM (NON-MELANOMA SKIN CANCERS) ISO/CIE 28077:2016

- **Our ACGIH TLV spectral weighting function S(λ) for UV is an action spectrum which envelopes skin and corneal action spectra.**
- **TLV documentation states:**



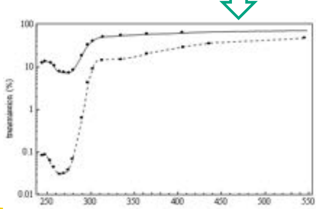
Limited published biological data below 250 nm.

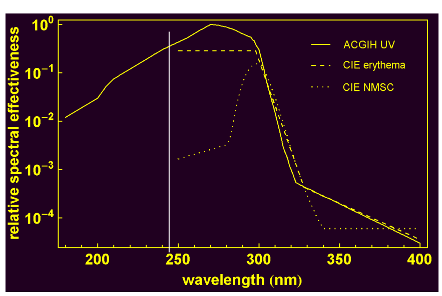
More than 100-fold added safety margin for the skin at 254 nm – ACGIH TLV - even greater at 222 nm

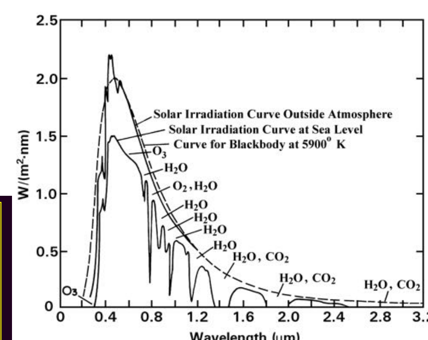
Is there a Realistic skin cancer risk?

The first Law of Photobiology – Photons have to be absorbed to produce an effect – and they have to reach the target Molecules

- TYPICAL CONCERN – If UV-C has highest photon energy why is it not more phototoxic and pose a greater severe skin cancer risk!?
  - UV-B photons are less energetic but they penetrate deeper
- Bruls transmission measurements





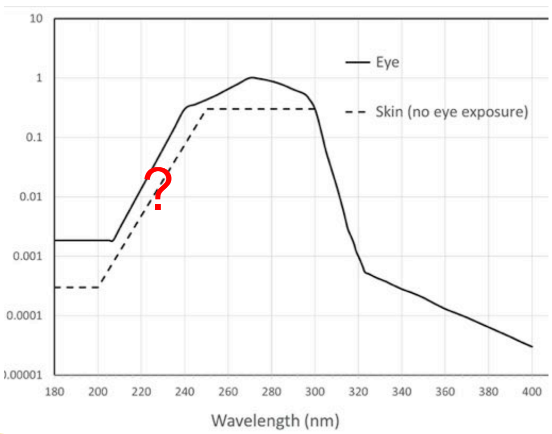


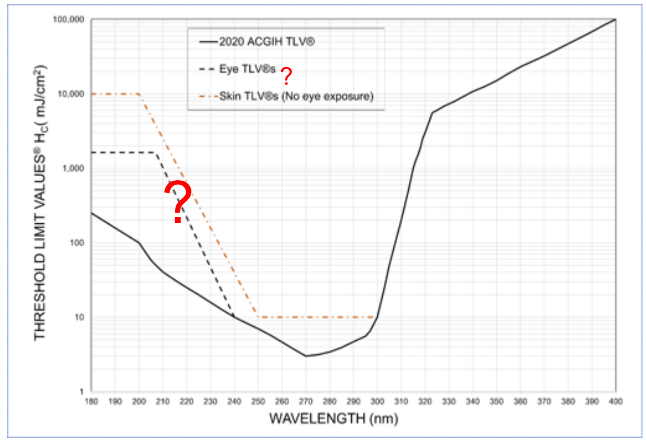
Sunlight spectrum – only trace amounts of UV-B reach ground level and no UV-C at all (Sliney & Wolbarsht, 1980)

See: CIE 187:2010 – UV-C Photocarcinogenic Risks from Germicidal Lamps

A Possible Adjustment of UV-C Exposure Limits

- As one example: Separate out Skin and Eye Limits?

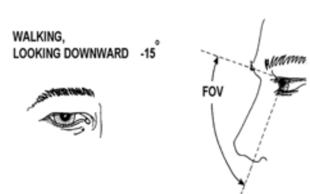




Safety – UV Measurements for Ocular Exposure

- If using a UV-Hazard irradiance meter, place an 80º cone hood (baffle) over the detector and direct the cone in the direction of tasks and actual viewing conditions.
  - Why only 80º Field-of-View (FOV)?
    - The normal visual FOV only extends up to 40 – 55 and the normal gaze angle is – 15º
    - Oblique rays are heavily attenuated in skin
  - Apply time-weighted averaging (TWA)!

Hood with Optometer



SAFETY ISSUES - PHOTOTOXICITY

- The very aspect (photo-toxicity) that makes short-wave ultraviolet (UV) radiation an effective germicidal agent also is responsible for the unwanted side effects of erythema (reddening of the skin) and photokeratitis (“welder’s flash” or “snow-blindness”).
- Effects from overexposure to UV-C are fortunately transient
  - superficial cells of the eye—the corneal epithelium
  - most superficial skin layer—the superficial epidermis
  - Normal turn-over of these cells soon erase signs and symptoms
- CIE photobiological band, UV-C (100 nm - 280 nm)
  - BENEFIT #1: shallow penetration depths –skin and eyes
  - BENEFIT #2: strong bio-aerosol absorption
  - UV-C 222 nm is safer than 254 nm – degree of improved safety still under study

HISTORY: ULTRAVIOLET GERMICIDAL IRRADIATION (UVGI)

- UV inactivation of cells discovered in disinfecting surfaces in 1877,' for water in 1910, and for air in 1935.
- UVGI widely used in the 1940s – 1960s in health care facilities to disinfect air and to some extent surfaces.
- GUV in recent decades has been largely limited in the U.S. to water treatment facilities and hidden (shielded) in heating and air-conditioning ductwork, or used in biological labs.
- GUV currently being used in many countries to control airborne transmission of tuberculosis (TB).
  - Downes A, Blunt TP. The influence of light upon the development of bacteria. Nature. 1877;16(402):218.

SUMMARY OF HISTORICAL EXPERIENCE

- UVGI can be an effective infection-control measure to protect hazardous bioaerosols
- Widely used in the 1940s and 1950s to combat the spread of TB, polio, measles, and influenza
- Used until the late 1960s to reduce hospital acquired infections in operating rooms and TB wards.
- Complaints of photokeratitis (eye flash) by OR staff, who failed to wear eye protection resulted in removals from OR suites despite complaints by some surgeons at that time

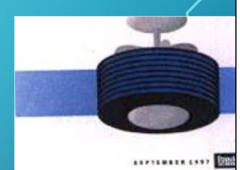
DNA is the target molecule for bacteria and many viruses, but also the susceptible molecules in eye or skin cells!

In SARS-CoV-2 corona virus, RNA is actually the target molecule and other amino acids like uracil may be important

TODAY – UVGI EMPLOYED IN CORONA-VIRUS CONTROL

Whole Room GUV in PRC

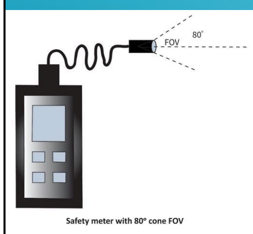
Upper-Air GUV in PRC

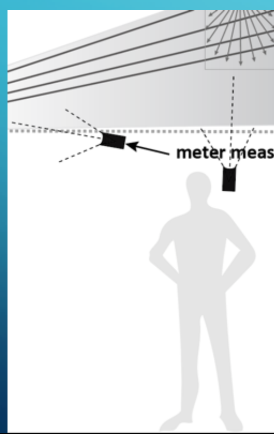


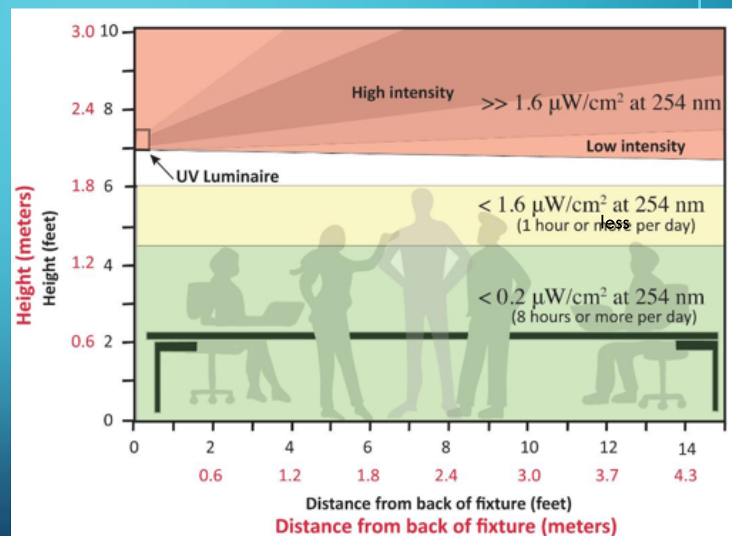
Upper-Air GUV Unit mounted in a patient room in a US Hospital

PROPER COMMISSIONING OF UVGI INSTALLATIONS

- Proper applications of the human exposure limits requires Time-Weighted Averaging (TWA) and an 80° cone Field-of-View



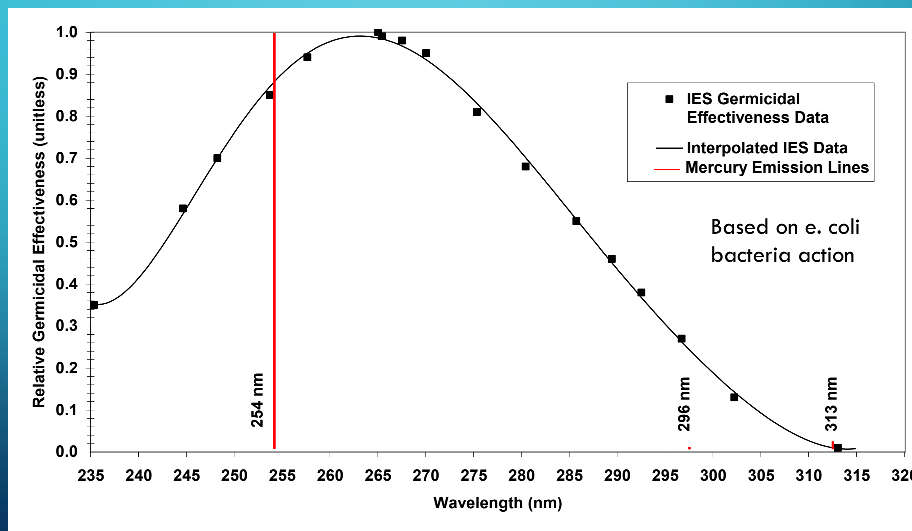




ANNEX – FOR QUESTIONS…

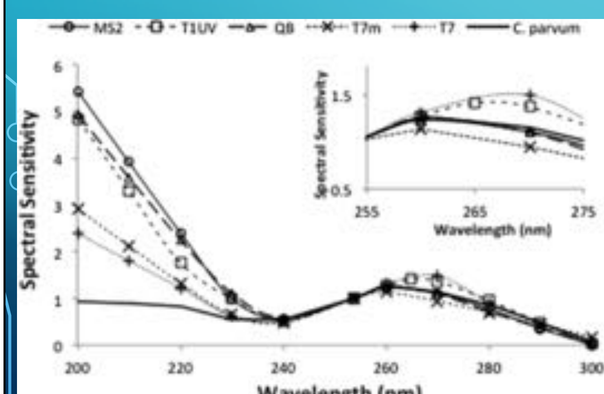
GERMICIDAL EFFECTIVENESS – THE ACTION SPECTRUM

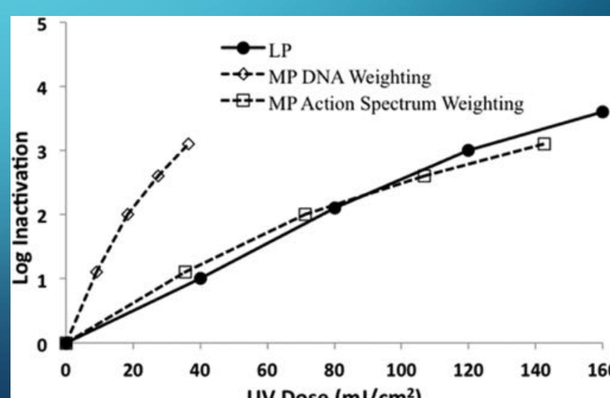
(DIN ACTION SPECTRUM VERY SIMILAR – DEPENDS ON TARGET)



SHORT-WAVELENGTH DOSE RESPONSE & ACTION SPECTRA

- More recent action spectra using a tunable Laser at NIST
- Initially a surprising increased efficacy at wavelengths below 230 nm where the historic action spectrum stopped!



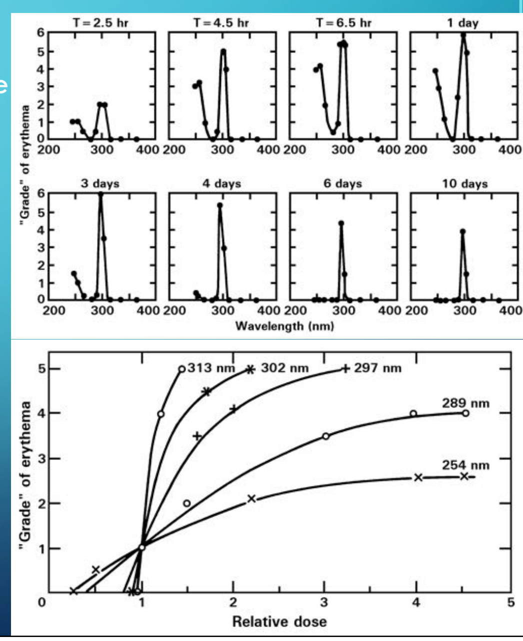


BUNSEN-ROSCOE LAW OF PHOTOCHEMISTRY

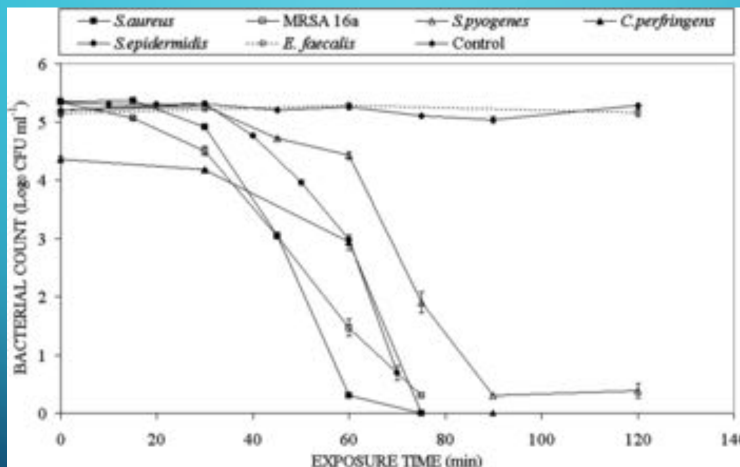
- The Bunsen-roscoe law of Photochemistry, or the rule of RECIPROCITY is very important in photobiological studies.
- Reciprocity of dose-rate E and duration t of exposure:
  - $H = E \times t$ = "exposure dose"
- Reciprocity may break down for very short exposures (non-linear interactions)
- Reciprocity breaks down for very lengthy exposures because of cellular repair or cellular death and replication
  - Generally hours for threshold skin injury (erythema) and corneal injury (photokeratitis)

UV EFFECTS ON THE SKIN - ERYTHEMA (SKIN REDDENING)

- Surprisingly, one of the most careful and complete studies of the action spectra and time course of ultraviolet erythema was conducted by Hauser & Vahle at Siemens (Munich) in 1929!
- They show that severity was greatest in the UV-B and least severe in the UV-C (254 nm)
- The time course of UV-C (254 nm) was much shorter than UV-B (313 nm)
- They showed that the time and end-point of their determination made a great difference.



THE 405-NM STUDIES OF MACLEAN – 2009 GLASGOW, SCOTLAND)



- Promising, but Exposure was 3600 s (1 h) at 10 mW/cm^2 = 36 J/cm^2
- This is clearly not direct DNA damage but a photodynamic effect with other molecules

SAFETY-2: DOWNWARD UV-C RADIATION CAN DISINFECT EXPOSED SURFACES IN AN **UNOCCUPIED ROOM**.

- A higher horizontal irradiance could be permitted than with a vertical (wall-facing) irradiance using the 80^o acceptance angle recommended by ACGIH.
- However, one wants to be cautious about the upward-stare time.
- The eye is well adapted to outdoor exposure from overhead UV-B.
- Equivalent UV irradiance at noontime in the summer is several μW/cm^2
- This is blocked by the upper lid
  - Lid lowers in sunlight
  - Brow ridge also limiting exposure.
  - Would this ever be accepted!?