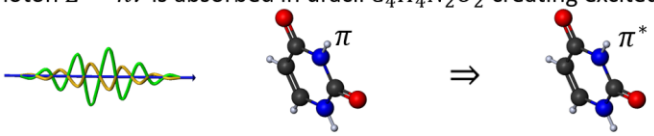
Optical power density measurement system in units of $\frac{mW}{cm^3}$

Tom Dunbar CTO uvcPhyzx Corporation 5-2023

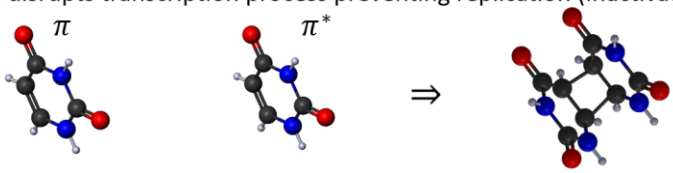
In February 2020 we surmised that the principal transmission method for the coronavirus was as an inhaled aerosol and began a research project to determine the best method for aerosol viral inactivation using UV-C light. Unfortunately most of the prior research has been done using UV-C exposure of viral particles contained on the surface of petri dishes and results evaluated with Irradiance values measured in units of $\frac{\mu W}{cm^2}$ combined with the experiment duration yielding exposure values in units of $\frac{\mu J}{cm^2}$. Surface based experiments are not suitable for evaluating inactivation characteristics for aerosolized situations. Optical power density measurements are needed, especially now that far UV based 222 nm proposals aim to continually radiate both air and occupants in interior spaces. To understand why surface measurements are unsuitable we delve into the process of UV-C inactivation.

Our initial choice for inactivation is the 253.7nm line present in low-pressure high output mercury vapor amalgam lamps. The principal inactivation at this wavelength in RNA based pathogens is absorption of photons into the uracil base within the RNA structure. The process:

Photon $E = h\nu$ is absorbed in uracil $C_4H_4N_2O_2$ creating excited state π^*

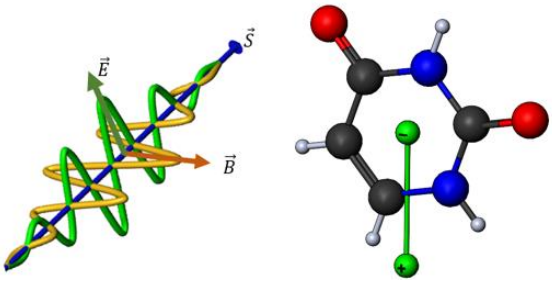


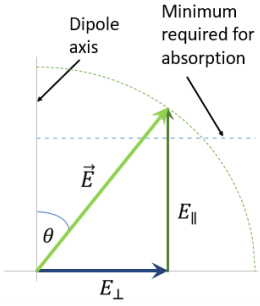
Normal state interacts with excited state forming uracil dimer $C_8H_8N_4O_4$ which disrupts transcription process preventing replication (Inactivated)



The timing of the photo-chemical reaction is a 10^{-15} second photon absorption into the uracil which causes an increase in the internuclear oscillation in 10^{-12} seconds necessary for the dimer formation reaction. If the reaction doesn't occur given proximity of rest state uracil bases, the π^*bases relax within 10^{-3}seconds. Our hypothesis is that the probability of inactivation is directly related to the population percentages of excited and rest state bases during a 1 millisecond convolution over the time a pathogen is within a device active region. Our goal is a population inversion.

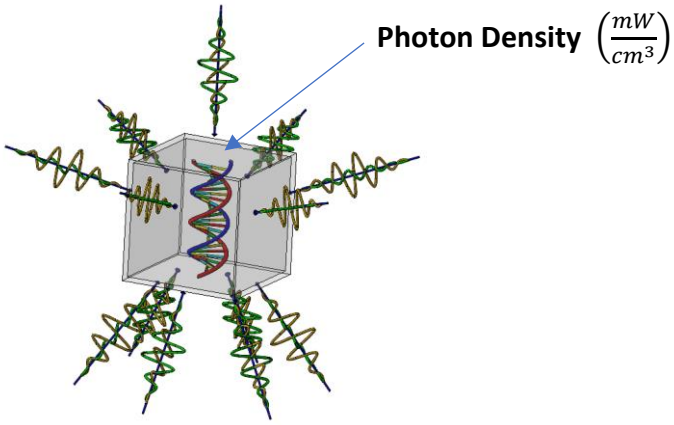
Only the parallel component of the photon electric field vector relative to the uracil dipole transition moment contributes to the probability of absorption. This establishes that the best attack orientation is for the photon electric field vector to be parallel to the dipole axis and the photon Poynting vector to be perpendicular.



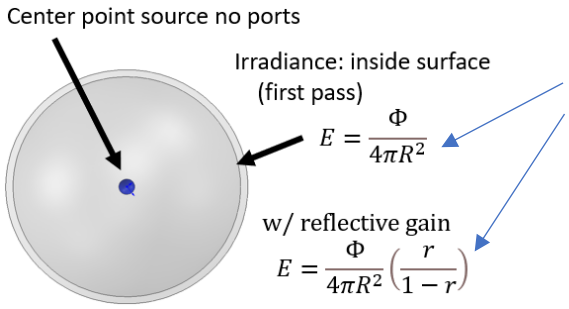


Given the random nature of bases within the RNA or DNA structure and the preferential orientation for probability of absorption, attacking a viral particle from a large percentage of possible attack angles simultaneously is preferred. Most UV-C inactivation systems attack from a singular or low number of angles such as the traditional "upper air" UV systems that have been in use for many years. In discussion with a colleague working at another UV-C based sanitization company he stated that they found hitting pathogens from two directions was more effective than hitting from one direction with twice the power.

In our work we make attempts to calculate the corresponding optical power density within our device designs and have labeled it Photon Density. We are developing a measurement capability that will relate to photon density and subsequently seek to work in collaboration with NIST to develop a standard method for calibration.



To enable a high number of attack angles designs must incorporate encompassing reflective surfaces and consider illumination source and port geometries. To gain some insight consider a point source located in the center of a highly reflective interior surface hollow spere.



- $\frac{1}{R^2}$ geometry factor
- Boyd[1] [Eqn. 5.6.1] derived in the section that describes integrating spheres.
- Contained flux is distributed within the volume.
- Smaller diameter provides higher Irradiance at reflecting surface.
- Real sources & ports reduce reflection gains.

The Photon Density for real systems that contain extended sources, ports for air flow into and out of the optical cavity and have complex cavity volume in which the flux is distributed is a difficult calculation through either mathematical integration or modeling and is an approximate value regardless. We define the constant that combined with source power provides the photon density as the device Flux Capacitance $\emptyset_c \left(\frac{1}{cm^3}\right)$.

Photon Density = Source flux * $\underbrace{(\text{geometry-port-source factor}) * \text{reflective gain}}_{\textbf{Flux Capacitance } \Phi_c \left(\frac{1}{cm^3}\right)}$ $\left(\frac{mW}{cm^3}\right)$

In electrical calculations, capacitance is a measure of the electron "storage" capacity of a device. As analogy the device optical cavities contain light generated by the source for some time "reusing" the photons as they pass multiple times through the gas where a probability of pathogen absorption exists. In a simplistic view, a 100-photon source optical ray passes through the cavity and 90 reflect from a 90% reflective surface, then 81,73,65,59,53. After just 6 reflections the 100 source photons result in 522 passes through the gas resulting in an increase of photon density of over 5x.

Every design will have a photon density that varies from a likely maximum in the cavity center to minimums which would occur at the boundaries of input and exit ports. In our current designs we employ a cylindrical cavity shape of volume $V = \pi R^2 L$ with a source -port factor, Sp_f, estimated at 0.6.

$$\Phi_c = \frac{Sp_f}{\pi R^2 L}\left(\frac{r}{1-r}\right) \quad \left(\frac{1}{cm^3}\right)$$

Capacitance values increase with a smaller cross section radius and shorter length, but this effects the time a pathogen is within the cavity for a desired cfm throughput. Density measurements within the cavity aid in assisting optimization of design parameters and provide necessary data for comparison / evaluation of UV-C based inactivation technologies prior to pathogen survival testing confirmation. Unfortunately most existing indoor air quality improvement systems rely heavily on HEPA filtration for certification testing but utilize petri dish results for claims of UV-C inactivation. This results in misleading UV-C inactivation performance claims.

Pathogen sensitivity to absorption varies as a function of wavelength. RNA based pathogens have a peak absorption at 258 nm and DNA based pathogens where the target is thymine has peak absorption at 263 nm with curves well defined in the literature. We define Germicidal Radiance as the integration of source times pathogen sensitivity over the effective wavelength range. A photon density measurement capability enables replication of prior experiments to establish multi attack angle decay constants for aerosolized pathogens.

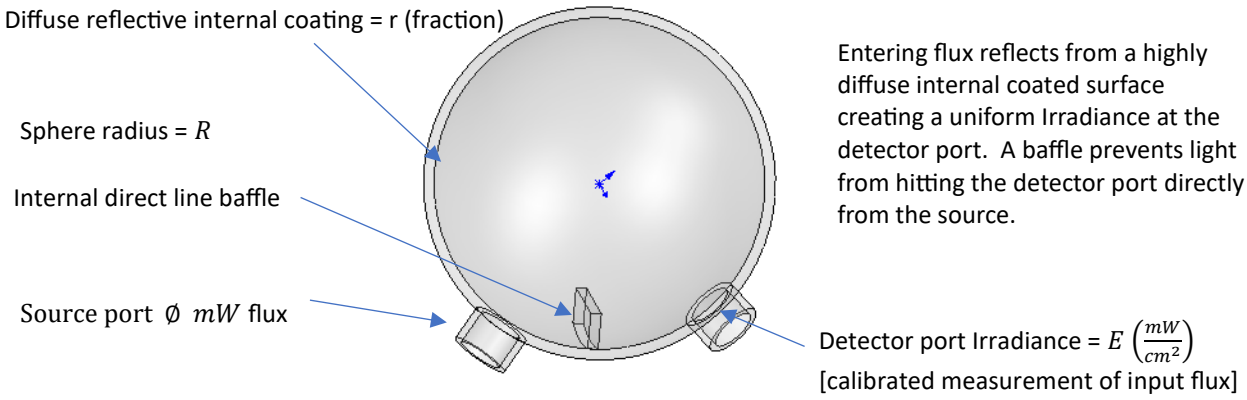
Germicidal Radiance:

$$P_{eff} = \int_{\lambda_1}^{\lambda_2} P_{source}(\lambda) S_{pathogen}(\lambda) d\lambda$$

- Photon Density $P = P_{eff}\,\Phi_c \qquad \left(\frac{mW}{cm^3}\right)$
- Pathogen Exposure $E = Pt \qquad \left(\frac{mJ}{cm^3}\right)$
- Single pass survival fraction $S = e^{-k'E}$
- k' = multi attack angle pathogen specific decay constant

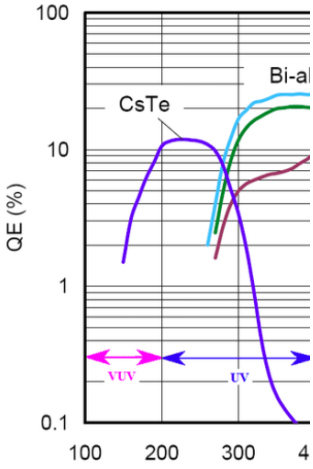
It should be noted that uracil and thymine absorption are not the only mechanisms that contribute to pathogen inactivation. In the far UV such as at 222nm, proteins are broken down that reduce the pathogens' ability to replicate. The sensitivity to multi angle attack situations for this process needs to be investigated. This is important to quantify since many far UV installations will have multiple devices each providing a different angle of attack. Optical detectors that measure only surface irradiance all provide incorrect data due to the cosine fall off from sources not normal of the detector. Cosine correction detectors provide some assistance but still relate to a surface value and can only provide some insight for one half of the possible attack angles on a pathogen within the air in a room or enclosed exposure chamber.

To determine an accurate photon density within a relatively small cavity cross section a small measurement probe is needed. The probe itself will have an impact on reflected light and "shadows" created may reduce density by blocking light from the source on its first pass. It is also required that the probe accept light from many angles. Our measurement device design returns to the optical integrating sphere as a starting point.



Larger spheres have less calibration error due to a lower impact of the direct line baffle and lower percentage of port area compared to the total internal surface area. In one embodiment of our patent pending design an optical quality fused silica substrate shown below left is plated with aluminum in a process that provides voids in the plating with the desired diffraction angle aperture size and distribution.

Diffraction at each entering aperture replaces the diffuse reflection nature of traditional integrating spheres. High angles of diffraction also greatly reduce the effect of a source having direct line of sight to the exit detector port. Multiple reflections within the quartz structure provide a further integration of flux incident on the exit shaft cross section from each entrance aperture. The integrated Irradiance incident on the shaft intersection to the entrance sphere light pipes out for detection. A Cesium-Telluride photomultiplier tube with pico-ammeter photocurrent measurement is proposed for the prototype system. The overall length goal is 600 mm.



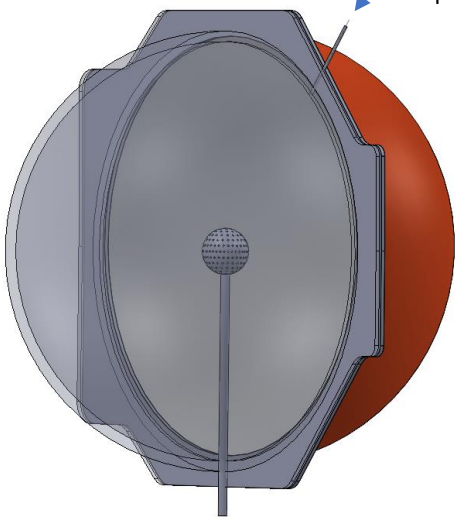
Many fundamental radiometry texts begin the definition of radiometric quantities with a discussion of the energy contained in a radiation field. Boyd[1] defines energy density as: $u = \frac{\partial Q}{\partial V}$ $\left(\frac{J}{m^3}\right)$ [Eqn. 2.1]. Since we are interested in the absorption by pathogens within this field it is imperative to separate the optical power density from time since in sanitization processes the aerosolized particles are moving quickly through the field especially in closed systems contained within ductwork. The Photon density measurement provides data that can be combined with pathogen particle velocities to establish Exposure values that can be used to compare systems and predict performance.

The concept of multiangle attack and measurement has long been in use for biology experiments to evaluate what is termed the “Scalar Irradiance” within organic materials such as plant, animal tissue or algae solutions. Biospherical Instruments produces a set of instruments that measure scalar irradiance for environmental monitoring. The most popular is the QSL-

100. These devices unfortunately are not suitable for work in the far UV 200-300 nm range. In addition, the measurements use a surface-based unit for a volume-based situation. Our device enables measurements in the critical 200 to 300 nm range and provides the correct unit for optical power density of $\frac{mW}{cm^3}$.

A further benefit is the use of this measurement system within spaces where UV-C illumination is desired in conjunction with occupants. This enables a determination if levels are sufficient for inactivation or exceeding recommended dosages for human exposure. Surface detector measurements are not as suitable given errors introduced by off axis sources and reflections within the occupied volume.

Proposed calibration configuration:



A standard Deuterium lamp focused on a quartz fiber carriers UV-C light into the sphere at adjustable angles with respect to the detector shaft axis. Photocurrent detector measurements compared with angles will characterize the device orientation sensitivity.

A monochromator between source and sphere would enable wavelength specific system evaluation. Goniometry will be used in initial evaluation of source to device orientation uniformity utilizing our UVC linear array component consisting of 10 265 nm 10 LEDs.

Author background: Tom Dunbar: MS Optical Engineering University of Rochester (84), Kodak R&D Engineer responsible for spectroradiometer calibrations & Image Quality prediction models for high altitude systems. Westinghouse Development engineer Electron Optics design & measurement systems for electron / phosphor photon efficiencies. Professor of Physics emeritus State University of New York Corning Community College. Inventor: US Pat 11357882. Single pass inactivation system to evaluate k' constants SyracuseCoE project 2023. CTO uvcPhyzx Corp.

1 Boyd, R. (1983). Radiometry and the Detection of Optical Radiation. Wiley