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COMMISSION INTERNATIONALE DE L'ECLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

TECHNICAL REPORT

ULTRAVIOLET AIR DISINFECTION

CIE 155:2003

UDC: 612.014.481
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Descriptor: Action of radiation
Air cleaners

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The International Commission on Illumination (CIE) is an organisation devoted to international co-operation and exchange of information among its member countries on all matters relating to the art and science of lighting. Its membership consists of the National Committees in 38 countries and one geographical area and of 4 associate members.

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Tagungen werden alle vier Jahre abgehalten, in der die Arbeiten der Divisionen überprüft und berichtet und neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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COMMISSION INTERNATIONALE DE L'ECLAIRAGE
CIE Central Bureau
Kegelgasse 27, A-1030 Vienna, AUSTRIA
Tel: +43(0)1714 31 87 0, Fax: +43(0)1713 08 38 18
e-mail: ciecb@ping.at
WWW: <http://www.cie.co.at/>

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This Technical Report has been prepared by CIE Technical Committee 6-35 of Division 6 "Photobiology and Photochemistry" and has been approved by the Board of Administration of the Commission Internationale de l'Eclairage for study and application. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory. The latest CIE proceedings or CIE NEWS should be consulted regarding possible subsequent amendments.

Ce rapport technique a été élaboré par le Comité Technique CIE 6-35 de la Division 6 "Photobiologie et Photochimie" et a été approuvé par le Bureau de la Commission Internationale de l'Eclairage, pour étude et emploi. Le document expose les connaissances et l'expérience courantes dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tout les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire. Il faut consulter les plus récents comptes rendus de la CIE, ou le CIE NEWS, en ce qui concerne des amendements nouveaux éventuels.

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The following members of TC 6-35, "UVR Disinfection" took part in the preparation of this technical report. The committee comes under Division 6 "Photobiology and Photochemistry".

Members:

Name	Country
A. Cabaj	Austria
K. Jalink	The Netherlands
K. Kohmoto	Japan
R. E. Levin	USA
E. A. Nardell	USA
R. L. Riley †	USA
G. J. van den Beld	The Netherlands
R. L. Vincent, Chairman	USA

Advisors:

Name	Country
P. W. Brickner	USA
W. T. Chaisson	USA
T. Dumyahn	USA
M. W. First	USA
S. N. Rudnick	USA
D. H. Sliney	USA

† Deceased

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ULTRAVIOLET AIR DISINFECTION

SUMMARY

In the 1870s, using solar radiation as the ultraviolet radiation (UVR) source, studies were initiated to understand the molecular changes in living organisms produced by UVR absorption. In the 20th century, with the invention of electric mercury-vapor arc lamps, a controllable, economical source of germicidal, short wavelength, 253,7 nm UVR became available. Systematic study of UVR impacts on biological systems across several disciplines began, using germicidal UVR lamps. UVR impacts on biological systems have been studied to provide understanding for protection of human beings from hazardous exposure and the capacity of UVR to stem the spread of infectious diseases by inactivating microorganisms in food, water and air. Since global incidents of bioterrorism have escalated from the late 20th century into the 21st, mitigation of biological threats in congregate settings within buildings has taken on further significance for UVR air and surface disinfection and decontamination. Additionally, multi-drug resistant strains of airborne infectious agents have been increasing. *Mycobacterium tuberculosis* (TB) is the most prominent. With 2 billion persons infected by TB and 2 million dying per year, it is the single largest adult killer among infectious diseases. A greater understanding of the potential of UVR air disinfection is needed. This report summarises the present state of knowledge of UVR air disinfection and provides recommendations for future work in research, standardization and testing procedures.

STERILISATION DE L'AIR PAR RAYONNEMENT ULTRAVIOLET

RESUME

Dans les années 1870, utilisant le rayonnement solaire comme source de radiations ultraviolettes (RUV), des études ont été entreprises pour appréhender les modifications moléculaires induites par l'absorption des RUV chez les organismes vivants. Au 20^e siècle, avec l'invention de lampes à arc électrique à vapeur de mercure, on a disposé d'une source de RUV germicide, économique et contrôlable, de courte longueur d'onde (253,7 nm). Une approche multidisciplinaire systématique des effets des RUV sur les systèmes biologiques a débuté, utilisant des lampes émettant les RUV germicides. Les effets des RUV sur les systèmes biologiques ont été analysés afin de mieux comprendre leur mécanisme d'action pour mieux protéger l'homme vis à vis des risques liés aux expositions UV et explorer l'efficacité des RUV à enrayer l'extension des maladies infectieuses en inactivant les micro-organismes dans les aliments, l'eau et l'air. Avec les incidents de dimension planétaire liés au bio terrorisme qui se sont multipliés depuis la fin du 20^e siècle jusqu'au début du 21^e, la réduction des menaces biologiques par des dispositifs complexes, dans les bâtiments, a pris une signification spécifique avec la décontamination et la désinfection de l'air et des surfaces par les RUV. De plus, les souches d'agents infectieux aéroportés, multirésistantes, se sont multipliées. L'infection par la mycobactérie tuberculeuse (BT) en est la meilleure illustration. Avec deux milliards de personnes infectées par le BT et deux millions de personnes en mourant chaque années, on est en présence d'un agent tueur de personnes adultes le plus important parmi les maladies infectieuses. Une meilleure compréhension du potentiel de la désinfection de l'air par les RUV est nécessaire. Ce rapport résume l'état actuel des connaissances dans la désinfection de l'air par les RUV et fournit des recommandations pour de futurs travaux de recherche, de standardisation, et de procédures d'évaluation.

LUFTDESINFEKTION MITTELS ULTRAVIOLETT-STRAHLUNG

ZUSAMMENFASSUNG

Im Jahrzehnt nach 1870 wurden Studien zum besseren Verständnis der molekularen Änderungen, die durch die Absorption von UV-Strahlung in lebenden Organismen entstehen, initiiert, wobei die Sonne als Quelle der UV-Strahlung diente. Im zwanzigsten Jahrhundert wurden mit der Erfindung der elektrischen Quecksilberdampflampen kontrollierbare und ökonomische Quellen bakterientötender UV-Strahlung mit einer Wellenlänge von 253,7 nm verfügbar. Unter Verwendung bakterientötender Lampen begannen multidisziplinäre und systematische Studien über den Einfluss von UV-Strahlung auf biologische Systeme. Der

Einfluss von UV-Strahlung auf biologische Systeme wurde untersucht, um das Verständnis für die Schutzmöglichkeiten von Menschen vor gefährlichen Expositionen zu erhöhen, und um die Möglichkeit, mittels UV-Bestrahlung der Ausbreitung von Infektionskrankheiten durch Inaktivierung von Mikroorganismen in Nahrungsmitteln, Wasser und Luft Einhalt zu gebieten, zu verbessern. Da die Häufigkeit des globalen Auftretens von Bioterrorismus seit dem Ende des 20. Jahrhunderts und dem Beginn des 21. Jahrhunderts zugenommen hat, gewann die UV-Desinfektion und Dekontamination von Luft und von Oberflächen zusätzliche Bedeutung für die Reduzierung von biologischen Gefährdungen bei Versammlungen in Gebäuden. Außerdem kommen mehrfachresistente Stämme luftgetragener Infektionserreger häufiger vor, davon ist *Mycobacterium tuberculosis* (TB) der Wichtigste. Mit jährlich 2 Milliarden mit TB infizierter Personen und 2 Millionen Todesfällen ist TB die häufigste Todesursache durch Infektionskrankheiten bei Erwachsenen. Ein tieferes Verständnis des Potentials von UV-Strahlung für die Luftdesinfektion ist notwendig. Dieser Bericht fasst den gegenwärtigen Stand des Wissens über die Luftdesinfektion mittels UV-Strahlung zusammen und bringt Empfehlungen für zukünftige Forschung, Normung und Testverfahren.

ACRONYMS AND ABBREVIATIONS

ACH	Air changes per hour
ACH _{eq}	Equivalent air changes per hour
AIA	American Institute of Architects
ACGIH	American Conference of Governmental Industrial Hygienists
ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
BCC	Basal cell carcinoma
BCG	Bacillus Calmette-Guerin
CDC	U.S. Centers for Disease Control and Prevention
CFD	Computational fluid dynamics
CFU	Colony formation unit
CIE	Commission Internationale de l'Eclairage
DIN	Deutsches Institut für Normung e.V. (German Institute for Standardization)
DOTS	Directly observed therapy short course
DNA	Deoxyribonucleic acid
HCW	Health care worker
HEPA	High efficiency particulate air (filter)
HSPH	Harvard School of Public Health
HVAC	Heating, ventilating, and air conditioning
MDR TB	Multi-drug resistant tuberculosis
MTB	Mycobacterium tuberculosis
MRC	South African Medical Research Council
NIOSH	U.S. National Institute of Occupational Safety and Health
NMSC	Nonmelanoma skin cancer
OR	Operating room
RH	Relative humidity
RNA	Ribonucleic acid
SCC	Squamous cell carcinoma
TLV	Threshold limit value
TUSS	Tuberculosis Ultraviolet Shelter Study
UVGI	Ultraviolet germicidal irradiation
UVR	Ultraviolet radiation

INTRODUCTION

Historically, the definition of terms, measurement method, spectral limits and beneficial applications of ultraviolet radiation (UVR) and ultraviolet germicidal irradiation (UVGI) began within the Commission Internationale de L'Eclairage (CIE) in the early 1930s (CIE, 1935).

Disinfection of air from airborne pathogens is commonly accomplished by ventilation (to dilute and remove infectious particles); high efficiency particulate air (HEPA) filtration (to capture infectious particles small enough to be inhaled); and ultraviolet germicidal irradiation (UVGI) [to damage deoxyribonucleic acid (DNA) of the microorganism to make it harmless] (CDC, 1994; Harm, 1980). Twenty-first century bioterrorism attacks have brought about an intense review of UVR disinfection application literature (air, as well as surfaces and water) for public health protection (Glanz et al., 2001; Gerberding et al., 2002; CDC, 2001b; Drazen, 2002; Committee on Science and Technology for Countering Terrorism, 2002). For treatment of some occupied areas (congregate settings such as homeless shelters, schools, auditoriums, office buildings and transportation centres), UVGI may have an important advantage over high rates of ventilation or filtration (Brickner et al., 2000; First et al., 1999b). As an environmental control, UVGI is applied to inactivate infectious agents in occupied rooms (by upper air disinfection); on surfaces (both in occupied and unoccupied spaces) and in ventilations systems (in-duct systems). Since the 1930s studies (Wells, 1935; Wells, 1955; Riley et al., 1976; Riley et al., 1989; Luckiesh, 1946) have shown that upper-room UVGI decreases the concentration of infectious airborne organisms in the lower part of the room. The medical profession was the first to endorse UV lamps for disinfection (CPM, 1948). Operators of surgical suites use UVGI to sterilize the operating field for patient infection control, as well as to cleanse room surfaces (Hart, 1960a, Hart, 1960b). Laboratory personnel handling infectious materials continue to use UVR sterilization techniques (Phillips et al., 1955). Some food-processing plants use ultraviolet radiation to preserve foods. Germicidal

ultraviolet lamps strategically placed in the upper room release short wavelength, 253,7 nm, UV-C energy, to damage bacteria and viruses floating on convection currents in rooms, rendering them harmless. Similarly, germicidal lamps are placed in air-ducts as well as portable, self-contained air moving devices to clean air of microorganisms. The germicidal effect prevents the reproduction of these infectious agents. Disease transmission is thus interrupted. Some of the infectious agents that cause human respiratory disease and that are susceptible to UVR air disinfection include tuberculosis, measles, adenovirus, glanders, influenza and probably smallpox.

2001 events in the United States created renewed interest in the possibility of using germicidal UVR to destroy anthrax spores released in the environment. These spores were of an aerodynamic size that allowed them to float on air currents and be recirculated through air-ducts. Transmission control would require surface and air decontamination for which, at present, there is no established basis for UVR application. There is little in the open literature on susceptibility of anthrax spores to UVR. What does exist is more applicable to surface disinfection. A study by Knudson (Knudson, 1986) suggests that spores are about 20 times more resistant to UVR than the vegetative form of *Bacillus anthracis*. Anthrax spores are inactivated by UVR in the same manner as other microbes, i.e., the survival fraction decreases as an exponential function of the UVR energy density. Consequently, to develop a meaningful disinfection protocol, an acceptable survival fraction is required. Such a reference standard has not yet been established. More important, UVR inactivation is *line-of-sight*. This indicates that UVR is a poor disinfectant of surfaces. Any shadowing, even on a microscopic basis, can preclude effective disinfection. As a suggestion of the UVR resistance of the spore form, an experiment of UVR sterilization on surfaces of aluminium, ceramic and wood surfaces by Dietz et al. (Dietz et al., 1980) concluded that in rare cases sterility could be obtained by a dose of $2 \times 10^4 \text{ J/m}^2$; however, in general a dosage over $2 \times 10^6 \text{ J/m}^2$ was not sufficient. Further study is needed to determine the potential of UVR inactivation of aerosolized anthrax spores. UVR is vastly more effective in control of *airborne* infection, compared to surfaces.

Studies of transmission of *Mycobacterium tuberculosis* (MTB) may provide clues on how to approach effective protection of public spaces from a wide range of airborne infectious agents. From the mid-1980s - with a resurgence of tuberculosis - to the present there has been increased concern over the globalized spread of strains of multi-drug resistant TB (MDR TB) (CDC, 2002a; CDC, 2002b; Farmer et al., 1999; Walton et al., 2000). While effective treatment of TB patients in developed and resource-limited countries through directly observed therapy short course (DOTS-plus) (Frieden, 2000) is the essential intervention in stopping its spread, there is another critically important aspect of the problem that has received little attention from governmental and non governmental agencies, - *infection control in congregate settings*. Every case of TB, MDR or otherwise, is the result of person-to-person airborne transmission. Transmission in congregate settings not only results in more efficient TB spread in the community, but also threatens the very health care workers (HCW) who are essential to the treatment of patients. Molecular fingerprinting has demonstrated MDR TB transmission in hospitals in South Africa and Argentina, resource-limited countries where late diagnosis, ineffective treatment, prolonged hospitalization, and lack of isolation facilities combine to assure spread between patients and between patients and health care workers. Patients being treated for drug-susceptible TB in Russian prisons have even become *reinfected* by MDR strains, proven by molecular fingerprinting. Health care workers, especially those who are HIV-infected, contract MDR TB in high-prevalence areas, and many have died (Espinal et al., 2001; CDC, 2001c; Friedman, 2001).

1. SCOPE

The terms of reference for CIE TC 6-35 are: To review the current status of using a form of ultraviolet radiation (UVR) for disinfection of air. Because of growing interest a brief section on surface disinfection is included.

2. ULTRAVIOLET RADIATION (UVR)

2.1 Properties

Ultraviolet radiation (UVR) is any radiant energy with a wavelength between 100 nm - 400 nm (see Figure 1). Ultraviolet (UV) is a portion of the electromagnetic spectrum and the radiation within this wavelength range is produced by the sun and by man-made sources. Photobiologists often use the division of the ultraviolet spectrum as given by the CIE: UV-A, 315 nm - 400 nm; UV-B, 280 nm - 315 nm; UV-C, 100 nm - 280 nm. The term UVGI (defined as ultraviolet germicidal irradiation) refers to the output of ultraviolet germicidal lamps and the systems that distribute the UVGI energy, i.e., UVGI fixtures.

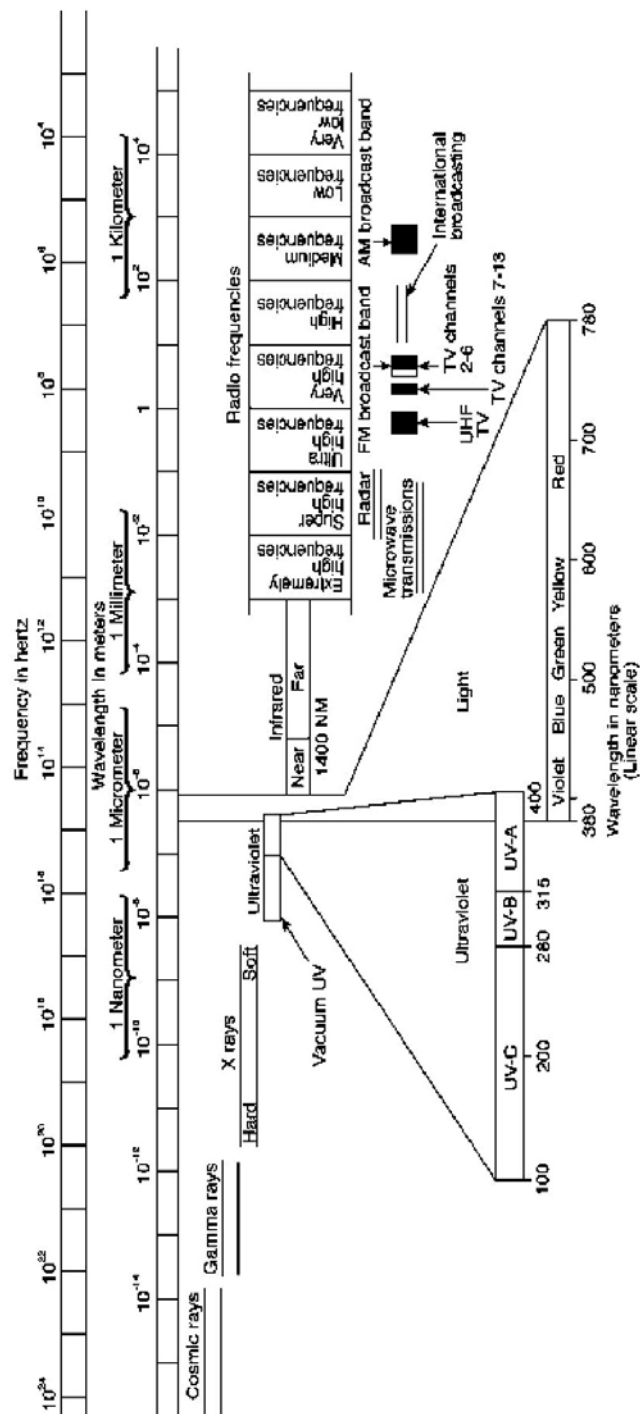


Fig. 1. Electromagnetic spectrum. Source: IESNA Lighting Handbook 9th Edition (IESNA, 2000b). Used with permission.

All UVR is composed of photons of energy. The energy of a single UV photon varies with wavelength and increases from long wavelengths to shorter wavelengths. In photochemistry one photon interacts with one absorbing molecule; therefore, theoretically, one photon can damage one DNA molecule (Harm, 1980; Sliney, 2000).

2.2 Radiometric definitions and quantification

A strong component of the work of CIE is the defining and standardization of radiometric terms. The following CIE radiometric quantities adapted from the CIE MORH handbook (ICNIRP/CIE, 1998) and used in the measurement of optical radiation hazards in photobiology, are briefly summarized here:

A. *Irradiance* (surface dose rate) and *radiant exposure* (surface dose) are quantities specifying power or energy incident upon a plane. As shown in Figure 2, these quantities are the dose rate (irradiance) and exposure dose (radiant exposure) that are the most fundamental dose quantities used in all of photobiology. The units most commonly used are W/cm^2 and J/cm^2 , respectively. SI units are W/m^2 and J/m^2 . $1 \text{ W} = 1 \text{ J/s}$.

B. *Fluence rate* and *fluence* are used in sophisticated studies, where the internal surface dose with backscatter is included. These quantities are used correctly most often in theoretical studies of dose distribution and where photochemistry at the molecular level in tissue is enhanced as a result of multiple scattering events in tissue. (See Section 2.4.) Unfortunately, these terms are frequently misused to mean irradiance and radiant exposure because the units of W/m^2 and J/m^2 are the same.

C. *Radiance* is an important quantity often used by physicists in specifying a source. Since the radiance is constant for any optical system, among others this quantity is a limiting factor for achieving high radiant exposure in the image of a light source provided by any lenses and reflective optics. For, example, a xenon-arc lamp has a very high radiance and its energy can be focused to produce a very high irradiance on a target tissue. By contrast, a fluorescent lamp tube has a much lower radiance, and its energy cannot be focused to a high concentration. Radiance is useful for specifying retinal hazards for lamp safety. The units are $\text{W}/(\text{m}^2 \cdot \text{sr})$.

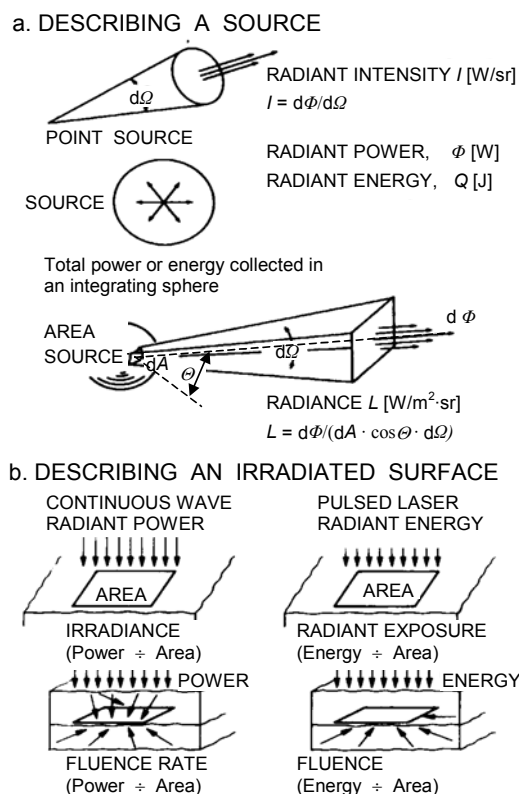


Fig. 2. Illustration of radiometric and fluence concepts. Source: CIE MORH (ICNIRP/CIE, 1998).

D. *Radiant Intensity* (power per solid angle) is used to indicate the radiated power in a given solid angle of a small source, where the distance is much larger than the size of the source. Although useful for specifying searchlights, it normally has very limited use in photobiology. The units are W/sr.

E. *Spectral quantities* (units per wavelength) are used for specifying the energy, power or irradiance per wavelength interval. When calculating a photobiologically effective dose the spectral quantity must be multiplied by the action spectrum. Examples: spectral radiant power, spectral irradiance, spectral radiant exposure, etc. The units for each quantity are modified by adding “per nanometre”, e.g., W/m^2 becomes $W/(m^2 \cdot nm)$.

F. *Photon (Quantum) quantities* (units in photons) are used primarily in theoretical studies and in photochemistry. In this case the radiant exposure is specified in photons/ m^2 and irradiance is specified in photons/($m^2 \cdot s$).

2.3 Dosimetry and the concept of photobiological dose

Ultraviolet germicidal irradiation follows the fundamental concepts of photobiology and photochemistry, including the following laws:

Inverse square law

As is true for visible light, the irradiance produced by an UVR point source is inversely proportional to the square of the distance.

Bunsen-Roscoe reciprocity law

Because the effect of UVGI follows the Bunsen-Roscoe law of reciprocity for photochemical reactions, the exposure time is inversely proportional to the radiant power for the same effect of inactivation on a given fraction of airborne organisms. In other words, the fraction of airborne organisms inactivated or “killed” depends on the fluence of UV and is not affected by reciprocal changes in irradiance and duration of exposure. Hence, $0,1 W/m^2$ ($10 \mu W/cm^2$) for 10 s is equivalent in killing power to $0,05 W/m^2$ ($5 \mu W/cm^2$) for 20 s.

Table 1. Summary of basic terminology used to quantify optical radiation.

Term	Internat symbol	Definition	SI unit	Synonyms and comments
wavelength ILV 845-01-14 (CIE, 1987)	λ	Distance in the direction of propagation of a periodic wave between two successive points at which the phase is the same.	m, nm	1 nanometer = 10^{-9} m
radiant energy ILV 845-01-27 (CIE, 1987)	Q_e	Time integral of the radiant flux ϕ_e over a given duration Δt .	J	Joule; 1 Joule = 1 Watt x 1 second. The index e means “energetic”, not weighted.
radiant flux (radiant power) ILV 845-01-24 (CIE, 1987)	ϕ_e	Power emitted, transmitted or received in the form of radiation.	W	Watt; 1 W = 1 J/s
irradiance (at a point of a surface) ILV 845-01-37 (CIE, 1987)	E_e	Quotient of the radiant flux $d\phi_e$ incident on an element of the surface containing the point, by the area dA of that element.	W/m^2	This is the “surface dose”-quantity for the irradiation of surfaces.
radiant exposure (at a point of a surface, for a given duration) ILV 845-01-42 (CIE, 1987)	H_e	Quotient of dQ_e , radiant energy incident on an element of the surface containing the point over the given duration, by the area dA of that element.	J/m^2	This is the “dose”-quantity for the irradiation of surfaces.
fluence rate (spherical irradiance) (at a point) ILV 845-01-40 (CIE, 1987)	$E_{e,o}$	Quotient of the radiant flux of all radiation incident on the outer surface of an infinitely small sphere centered at the given point, by the area of the diametrical cross-section of that sphere.	W/m^2	This is the “surface dose”-quantity for the irradiation of micro-organisms.
fluence (radiant spherical exposure) (at a point, for a given duration) ILV 845-01-45 (CIE, 1987)	$H_{e,o}$	Time integral of the fluence rate $E_{e,o}$ at the given point over the given duration Δt .	J/m^2	This is the “dose”-quantity for the irradiation of micro-organisms.

2.4 Measurement (irradiance, fluence)

Radiometer for measuring irradiance

A variety of physical instruments, called *radiometers*, can be used to measure radiometric quantities such as irradiance in the ultraviolet. These instruments are widely available as handheld field surveillance devices used for checking upper-room UVGI installations (Vincent, 1998) and as more complex spectroradiometers for rigorous measurement of lamps and lamp systems. Detailed techniques for measuring irradiance are described in the CIE Standard for Photobiological safety of lamps and lamp systems (CIE, 2002).

Actinometer and biodosimeter for measuring fluence

Because physical (as opposed to chemical or biological) instruments to measure fluence are not widely commercially available, chemical instruments called *actinometers* are used to measure fluence and fluence rate in the ultraviolet. An actinometer is defined as a chemical system (Rahn et al., 1999) or device which determines the number of *photons* in a beam integrally or per unit time. This term is commonly applied to devices used in the ultraviolet and visible wavelength ranges. For example, solutions of ferrioxalate can be used as chemical actinometers, while bolometers, thermopiles, and photodiodes are physical devices giving a reading that can be correlated to the number of photons detected. Actinometry is the process by which the number of photons emitted from a radiation source is determined using an actinometer.

If incident power arrives at a point from several sources and from different directions, the fluence rate can be measured using superposition, provided that the radiation from each source arrives through a reasonably small angle. Measure the individual maximum irradiance due to each source, i.e., on a plane normal to the incident radiation, without the contribution of the other sources. The fluence rate is the algebraic sum of the individual irradiances. This is valid even when the radiation is from opposite directions. However, if any source is large compared to its distance such that radiant power is arriving through a large solid angle, measuring irradiance as a component of fluence rate is not valid because of the cosine weighting in the irradiance measurement.

Another approach to developing a three dimensional measurement of the total UV dose received by an airborne microorganism is a *biodosimeter*. This approach, used to calibrate the effective dose of UV-C received by a microorganism during irradiation for water treatment (Cabaj et al., 1996) could be useful for airborne applications.

Fluence rate

Dimensionally the same as irradiance, *fluence rate* can be expressed in the same units, but the geometric interpretation is different from that of irradiance. Fluence rate is more general, and in the simplest case it reduces to irradiance. The fluence rate $E_{e,o}$ at a point in space is the omnidirectional radiant flux externally incident on an elementary sphere, per unit cross sectional area of the sphere.

$$E_{e,o} = d\Phi/dA \quad \text{W/m}^2$$

Φ is the total radiant power (W) incident on the sphere, and A (m^2) is the cross sectional area of the sphere. *Energy density* is fluence $H_{e,o}$, *power density* is fluence rate. For our purposes, the unit of $\mu\text{W}/\text{cm}^2$ often is more convenient than the unit of W/m^2 . All of this follows standard definitions related to radiation.

Explanation of the physical interpretation of fluence rate

3-dimensional objects do not respond spatially to incident power in the same manner as plane objects. Consider the irradiance on a small plane element produced by a radiant source at a large fixed distance. Rotate the source around the plane element from directly above the element through 90° to a point in the plane of the element. The irradiance on, and the power received by, the plane element, decreases from maximum to zero. Now replace the plane element with a small sphere and repeat the same movement of the source through 90° . The power received by the sphere does not change. Fluence rate is the metric related to power received by a 3-dimensional element from multiple directions.

Consider a single small source at a distance such that the incident radiation is reasonably parallel. Power incident on a plane area perpendicular to the direction of radiation divided by that area is irradiance. Now if a sphere were placed at the same location, it would intercept the same power as would a circular disk equal to a cross section of the sphere. Dividing this power by the cross sectional area of the sphere gives the same value as the irradiance measurement; the irradiance and the fluence rate are the same. If radiant power is not perpendicularly incident on a plane area, less power is received by that area. The irradiance will vary as the cosine of the angle between the direction of incidence and a normal to the area and is zero for angles greater than 90° . However, the sphere accepts power from all directions with equal weighting. This is the reason that fluence rate is the relevant metric for irradiation of 3-dimensional receiving elements.

In general, fluence rate is the required entity for evaluation of power density at a point (1) in proximity to a source, i.e., where the source subtends a large angle at the point, or (2) where multiple sources are located in different directions about the point. Otherwise, irradiance (as the limiting case for fluence rate) can be used to evaluate the power density at the point.

In summary, fluence rate is biological exposure dose rate that can only be measured by an actinometer or biodosimeter. Irradiance can actually be measured by physical instruments. While both quantities have the same units: traditional units of $\mu\text{W}\cdot\text{s}/\text{cm}^2$ and the SI units of J/m^2 , they have different uses. Fluence includes backscatter (multiple “hits”) to account for the 3-dimensional approaches to inactivating airborne microorganisms.

2.5 Converting units of incident energy

One common measurement in biological experiments is the energy incident per unit area normal to the UV beam at the position of the biological material. *Fluence* is the term for this quantity and has been expressed in the past literature in terms of ($\text{erg}\cdot\text{mm}^{-2}$) or ($\text{erg}\cdot\text{cm}^{-2}$). Today fluence is expressed in ($\text{J}\cdot\text{m}^{-2}$). The following relationship can be used to convert these units: $1 \text{ J}\cdot\text{m}^{-2} = 10 \text{ erg}\cdot\text{mm}^{-2} = 10^3 \text{ erg}\cdot\text{cm}^{-2}$

3. MICROORGANISMS

3.1 Types, characteristics and disease transmission

Microorganisms (also called microbes) are so small that they require a microscope to be seen. Some microbes can cause disease in plants, animals and humans. The four major genera of interest for UV air disinfection are bacteria, viruses, fungi and protozoa. By the late 19th century it was known that infectious diseases were caused by microbes; however, it was not until the early 20th century that it was determined that transmission of some infectious agents was through the air (Wells, 1955). Bacteria are composed of one cell, which contains DNA, may exist in a vegetative and spore form, and range in size from $0.2 \mu\text{m}$ to $1.5 \mu\text{m}$. Viruses are the smallest microbes (smaller than bacteria), are not cells (have no wall), contain one or more molecules of DNA or ribonucleic acid (RNA) (containing the virus's genes) and are surrounded by a protein coat. Fungi are primitive vegetables that can be found in the air, soil, plants, and in water. Certain types of fungi cause human disease, e.g. *Aspergillus fumigatus*, which can cause aspergillosis, a fungal infection of the respiratory system (NIH, 2001; Philips Lighting, 1992).

3.2 Droplet nuclei - Importance of particle size in disease transmission

Transmission of infectious disease is dependent on the concentration of infectious airborne particles that can be inhaled by a susceptible person. Wells (Wells, 1934) determined that droplets of various sizes expelled into the air when an infectious person coughs or sneezes, form aerodynamic droplet nuclei $1 \mu\text{m} - 5 \mu\text{m}$ in diameter through evaporation. These droplet nuclei can contain infectious particles and are light enough to remain airborne for extended periods of time. The human body has a hierarchy of defenses to protect the respiratory system from disease. In studies of the inhalation of particles, it has been found that the upper respiratory track almost completely screens particles over $10 \mu\text{m}$ in size, and that $5 \mu\text{m}$ particles were 80% screened. It was further determined that particles $5 \mu\text{m}$ and under were

deposited in the lung's alveoli (air sacs) (Hatch, 1961). If infectious microbial aerosols are inhaled into the lung's alveoli, they can cause respiratory infection (Wells, 1955). Riley found that infectious TB patients produced droplets containing tubercle bacilli when coughing, sneezing, or talking, which formed droplet nuclei. His guinea pig studies found that a single droplet nucleus may be capable of initiating pulmonary tuberculosis in highly susceptible hosts. This implies that there is no specific threshold air concentration below which transmission will not occur (Riley et al., 1959).

Studies of airborne microorganisms' viability, and hence their potential infectivity, have found that they are naturally affected by desiccation; therefore, high rates of relative humidity allow longer viability. Physical agents, such as oxygen, ozone and ultraviolet radiation and the reaction products they produce, decrease viability of microorganisms through physical and biological modification of lipids, proteins and nucleic acids (Cox, 1989). The usual criterion for microbe viability is its ability to form a colony.

Controlled studies of airborne microorganisms consider at least these fundamental questions:

- Can a viable droplet nucleus aerosol be generated for study?
- Do droplet nuclei remain viable long enough to be epidemiologically significant?
- Are particles small enough to reach the lung's alveoli?
- Can they be destroyed?

4. STANDARD AIR DISINFECTION TECHNOLOGIES

4.1 History

From the later part of the 19th century into the early decades of the 20th, the development of standards for public health focused on the reduction of the most significant cause of death, tuberculosis disease (TB). In this pre-antibiotic era physicians like Billings (Janssen, 1999) argued for a minimum amount of ventilating air (1 cubic meter/minute/occupant) in buildings for disease control, although it was not definitively shown that airborne transmission of respiratory disease was taking place.

In the 1930s, C. P. Yaglou at the Harvard School of Public Health (HSPH) developed the scientific basis for satisfactory indoor ventilation by having subjects in a control chamber detect body odour (Nardell, 2000). The work of William Firth Wells, an air hygienist, developed from participation of HSPH in the ventilation studies of Professor Yaglou (Wells, 1955). Wells' work led him to recommend a principle of air hygiene: ventilate for comfort and odour control; irradiate for airborne infection control (Riley, 1991). Richard L. Riley, a physician, began his lengthy collaboration with Wells at Harvard and Johns Hopkins, following their mutual interest in applying UVGI to interrupt the transmission of airborne disease (Wells, 1955).

Modern source control through identification and prompt treatment of infectious cases is the main control strategy but, as in the case of global TB, it is incompletely effective for the purpose of transmission control (Frieden et al, 1996). In the absence of immunization and effective detection and treatment, airborne transmission can be prevented by promptly eliminating infectious organisms through displacement (forced ventilation), by air filtration, or by killing or inactivating organisms with germicidal irradiation after they have been released into the air.

When room air becomes contaminated by an infectious source, microbes of the aerodynamic size described above can remain airborne, suspended for long periods, and move to other parts of a building, sometimes aided by recirculated air from mechanical ventilation systems. Prior to the development of high efficiency particulate air (HEPA) filtration techniques air hygienists relied on natural ventilation to dilute the source of contamination until natural die-off of the microorganisms occurred. The beginning point for the study of microorganism inactivation is a logarithmic plot of the natural die-off. With the invention of mechanical ventilation systems, fresh, out-door supply air was introduced into the room to replace contaminated air by dilution and exhausting room air to the outside. Ventilation and filtration techniques each have an important role as described below. What does not exist is a cohesive design methodology to integrate the equally important air cleansing capacity of ultraviolet air irradiation. Current research is needed to accomplish this goal.

4.2 Building ventilation and directional airflow as protection against airborne infection

A standard engineering approach to the control of airborne infection inside buildings consists of ventilation and directional airflow. Hospital isolation rooms, for example, employ high rates of ventilation to dilute and remove infectious particles, and directional airflow to prevent them from entering corridors or adjacent rooms. The higher rates however consume more energy, cause higher noise and drafts through a wind tunnel effect. Building codes mandate a range of ventilation rates for various public access buildings, requiring higher rates for schools, for instance, than for department stores.

Present ventilation standards are also under review because of indoor air quality issues that stem from reduced air changes per hour to conserve energy. The result has been a growing concern about indoor air quality. Now all building systems are being reviewed because of security concerns about potential malicious introduction of infectious agents. Architects, facility managers and health professionals are seeking methods to improve air quality and reduce the potential for spread of airborne infection in public buildings and homeless shelters (Wheeler, 1999; AIA, 2001).

Building ventilation is quantified both as outdoor air volume per unit time per person and as room air changes per hour (ACH), irrespective of occupancy. After the volume of air entering a room equals the volume of the room, one room air exchange is said to have taken place. In old buildings natural ventilation occurs through open windows and building leaks. Natural ventilation rates range from as little as one-fourth of an air exchange per hour (0,25 ACH) in a very tightly constructed building to several air exchanges per hour in one of less tight construction.

Public buildings in developed countries provide heating, ventilating, and air conditioning (HVAC) systems that usually condition and recirculate most of the returned air to save energy, exhausting some and replacing it with outside air in order to control odours, CO₂ build-up, and air contaminants such as smoke (ASHRAE, 2001). Because developers, architects and engineers are most familiar with these technologies, it is understandable that increased ventilation is often proposed to reduce airborne disease transmission in buildings (CDC, 1994).

4.3 Building ventilation with outside air - Quantitative considerations

In a room with only mechanical ventilation, air contaminated by a germ-laden cough or sneeze will wash out at a rate proportional to the amount of ventilation in ACH. When supply air is introduced at a fixed rate, the effect is equivalent to a steady decrease of the contaminant over time by dilution and removal; that is, each increment of supply air further dilutes the contaminant and pushes out an equal volume of contaminated air through the room exhaust. Therefore, even after an amount of supply air equal to one room volume (one air change) has passed through the room, some contamination remains. In fact, after the contaminated air has become well mixed, and assuming perfect mixing of the incoming air with the air already present, 37% of the contamination remains (ACGIH, 1992). After two air changes, 37% of the 37% of the initial air contamination (14%) remains in the room air. The contamination level decreases an equal fraction after each room air change. Thus, it requires about three room air changes to reduce the initial contamination concentration by 95% and about five room air changes to reduce the initial concentration by 99%, assuming no new contaminant has been added during this period. For most purposes, 6 ACH represents good ventilation practice and may be considered equivalent to approximately a 99% clearance rate in one hour. This exercise makes it clear that purging air contamination by conventional ventilation systems is a slow process under ideal circumstances but, in fact, room mixing is less than ideal and many more than six air changes are likely to be needed to reduce air contamination levels by 99%. Furthermore, it is common for additional contamination to be discharged into the room before the prior discharge has been eliminated. Prior to the bio-warfare anthrax attacks on the United States, ventilation rates for isolation rooms were undergoing critical examination. A CDC 2001 review of Guidelines for Infection Control in Health Care Facilities calls for epidemiologic evidence to support recommendations for specific air change per hour values (CDC, 2001a). The CDC and AIA Guidelines for health care settings are considering 12 ACH vs. normal ventilation rates of 6 for TB isolation rooms (CDC, 1994). Even with 12 ACH, purging of air contaminants by dilution is a slow process

that is difficult to control and unlikely to be fully protective when the source is strong and the exposure long.

Mid-20th century laboratory studies of UVGI efficacy compared the number of additional room air exchanges needed to produce the same clearance rate of microorganisms as that produced by the installed UVGI alone (Riley et al., 1989; Wells, 1942; Riley, 1988). Upper room UVGI for TB transmission control (based on actual room experiments with normal ventilation) produced inactivation of the microbe at an equivalent clearance rate of dilutional ventilation in the range of 10-20 air changes per hour. For other microorganisms, this rate of equivalent clearance will be greater or smaller depending upon its resistance to UVGI inactivation, as described below.

Further investigation to test UVGI efficacy in combination with different ventilation systems is needed. For example in the United States new energy efficient buildings have often used variable volume systems rather than constant volume systems. In these buildings the room air supply is not introduced at a fixed rate. Now the most recent trend in the US is to follow the European approach utilizing displacement ventilation.

While experimental testing is still required, the efficacy of upper-room UVGI when used with displacement ventilation systems can be judged based on two factors: (1) how well UVGI kills microbes in air that is extracted from a room and subsequently returned and (2) how much of the air in the lower occupied portion of a room has previously passed through the irradiated upper portion of a room without leaving the room.

Upper-room UVGI would likely be extremely effective for killing microbes in the extracted air because all of the air must pass through the upper irradiated portion of the room prior to being extracted. On the other hand, upper-room UVGI would not be effective for killing microbes in the lower occupied portion of a room unless the displacement ventilation was less than perfect, that is, some of the irradiated air in the upper room is returned to the lower room due to vertical mixing.

4.4 Air filtration

High efficiency particulate air (HEPA) filters remove over 99,97% of airborne particles that arrive at the filter media (First, 1991). HEPA filters, often used for infection control, are tested with an aerosol containing monodisperse particles 0,3 µm in diameter, the most penetrating particle size. Filtered recirculated air can be substituted for a portion of outside air, avoiding the cost of heating, cooling and dehumidifying outside air. The limitations of HEPA filtration for air disinfection are similar to those of increasing building ventilation rates to control transmission of infectious diseases, i.e., the need for high levels of progressively less efficient air changes. Also, HEPA filters generate resistance to airflow, necessitating more powerful fans that produce noise and vibration. Filters are costly and must be changed periodically. To be fully effective, HEPA filtration systems must not have holes or gasket leaks. They require careful routine maintenance (DHHS, 2002), as do all systems that are counted on to perform a critical function. Another limitation particular to portable air filtration units is the potential to re-entrain already filtered air because the unit's intake and exhaust locations are usually necessarily close to one another. This *short-circuiting* reduces the efficiency of air disinfection by HEPA filtration.

4.5 Irradiation of the air

Following his discovery of disease transmission by infectious droplet nuclei, Wells began investigations of methods to inactivate the microorganisms. Wells' classic experiment (1934) was the first to expose airborne bacteria to ultraviolet germicidal irradiation under carefully controlled conditions. He found a rapid (within a minute) destruction of a B. Coli aerosolized broth when exposed to germicidal ultraviolet irradiation (Wells, 1935). These studies were the foundation of air irradiation for infection control.

5. BIOLOGICAL EFFECTS OF UVR

Several factors affect the susceptibility of a microorganism to inactivation by UV radiation. Normally the level of effectiveness of UV dose is determined by survival of colony formation

units (CFUs) of microorganisms exposed in various test media (aerosols, plates, water). Results from one medium to another are not comparable. This report is limited primarily to discussions of aerosols, with some surface (plate) studies relevant to decontamination strategies of recent interest. Studies of microbe survival vs. UV exposure have investigated natural repair processes (photoreactivation and dark recovery), particle size, and moisture barriers to UV-C penetration as well as the microorganism's structure.

5.1 Action spectra for DNA UVR absorption

A photobiological action spectrum in its simplest form is a chart of effect (some bioresponse) as a function of wavelength. Gates reported the bactericidal action of ultraviolet "light" energy as early as 1929 (Gates, 1929). He showed that the cell death of bacteria closely followed the absorption spectrum for nucleic acids (see Figure 3). Absorption is the transfer of energy from an electromagnetic field to a molecular entity. Based on these early experiments, in 1935, Committee 41 of the International Commission on Illumination proposed the bacterial action spectrum shown in Figure 4 (CIE, 1935). It was conclusively proven several decades later that absorption spectra in the UV wavelength range follows the absorption of DNA. These studies have established the germicidal effect of ultraviolet energy. Collections of action spectra for various organisms exist (Calkins et al., 1979), in the form of a number of slightly differing curves and there is no international consensus for a standard UV germicidal action spectrum curve for microorganisms, as every microorganism may have its own. CIE TC 6-46 is reviewing the data to develop a recommendation for adoption of a standard UV germicidal action spectrum. Figure 5 (based on Table 2) illustrates bactericidal action spectra currently in use, where relative germicidal efficiency is defined at a limited number of wavelengths. The smooth curves have been provided by interpolation. The IESNA response (IESNA, 2000b) is from the 1934 work of Coblenz and Stair based on *Escherichia coli*, and the DIN curve is from the already withdrawn DIN 5031-10:1979-11 (DIN, 1979).

While our discussion is primarily on UV's impact on DNA, UV works in a similar way upon single stranded ribonucleic acid, RNA, that is integral to the viability of microorganisms such as viruses. Sufficient absorption of quanta of UV photons by a microorganism's DNA and RNA results in photochemical destruction. In RNA, hydrates and uracil dimers have been observed which can cause inactivation of RNA (Schechmeister, 1991). DNA in a double-stranded helix (see Figure 6) is linked together by a sequence of four constituent bases (adenine, cytosine, guanine and thymine), which are paired (adenine with thymine and cytosine with guanine) and held together by hydrogen bonds. These hydrogen bonds hold the DNA double helix together. Of the four bases, thymine undergoes a unique photochemical reaction. Absorption of UV radiation produces various photoproducts through a photochemical process which causes the formation of thymidine-thymidine dimers, DNA-protein and protein-protein cross linking as well as fragmentation and Maillard polymerization reactions of amino acids and sugars. Thymine dimers form when one of two thymine bases located adjacent to each other absorbs a UV photon. This leads to formation of a chemical bond between the two thymines (called a thymine dimer). This chemical bonding disrupts the structure of the DNA, so that if enough thymine dimers are formed, the DNA cannot replicate in cell mitosis (division). This, then, is the fundamental mechanism of UV disinfection (Harm, 1980; Bolton, 1999). The importance of these findings is that UV irradiation can kill or inhibit the growth of many microbes (including bacteria, viruses, fungi and protozoa) which are known to cause disease in humans and animals.

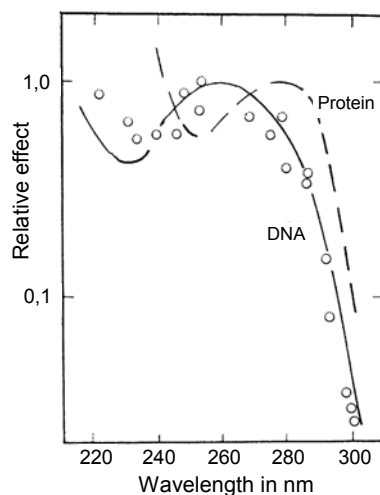


Fig. 3. Absorption spectra of DNA (solid line) and protein (dashed line) of UV. Cell death of unspecified bacteria (data points) follow DNA absorption, not protein absorption. Source: CIE MORH (ICNIRP/CIE, 1998).

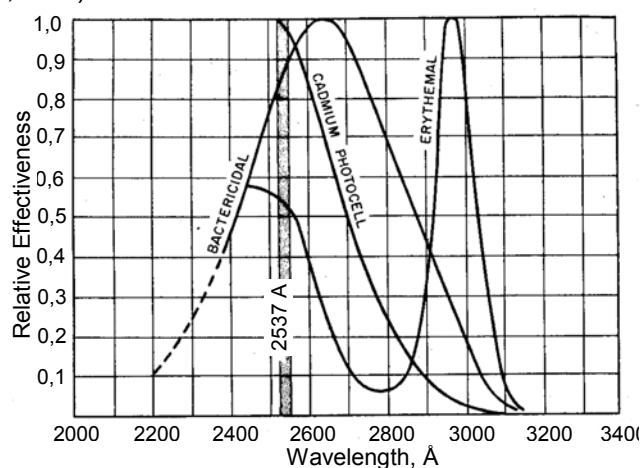


Fig. 4. Proposed CIE 1934 germicidal and erythral action spectra. Source: CIE Compte Rendu (CIE, 1935).

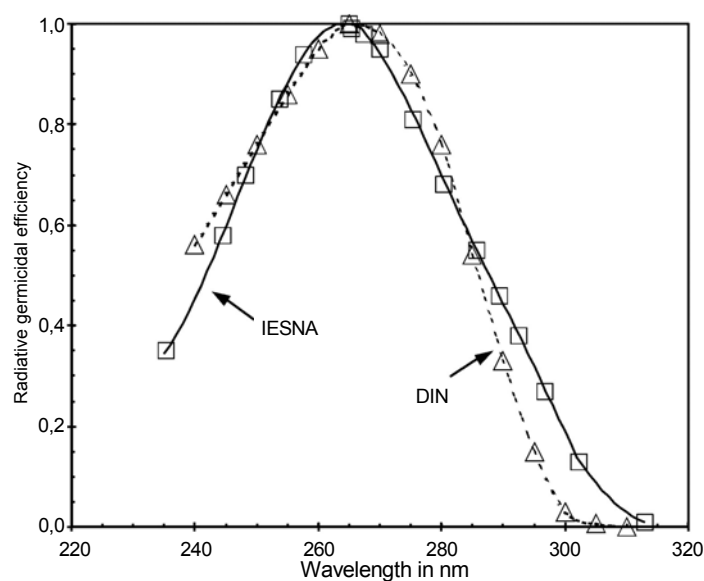


Fig. 5. Standard germicidal response curves (Data from Table 2).

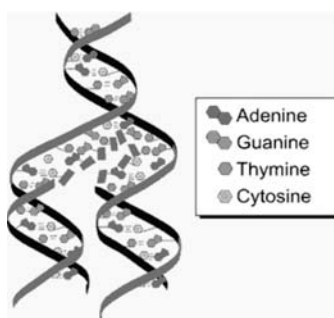


Fig. 6. DNA's two stranded double helix and constituent bases. Sufficient UV absorption breaks the hydrogen bonds between the bands rendering the microorganism harmless.

UV-C irradiation either eliminates or limits the organism's ability to reproduce or be repaired. The peak of germicidal effectiveness is in the UV-C near 265 nm as shown in Figure 5. Low-pressure germicidal lamps produce about 85% of their radiant output in UV-C, 253,7 nm energy that is close to the peak of germicidal efficiency, 265 nm. Many forms of microbes have been rigorously studied in the laboratory to determine the fluence of UV-C necessary to inactivate a given fraction for each pathogen. Often, these are reported for 90% kill (inactivation, 10% survival), as a way to facilitate comparisons.

Table 2. Standardized germicidal response functions (DIN, 1979; IESNA, 2000b). Used with permission.

Defined Tabulated Values				Fitted Curves		
Wavelength nm	DIN Rel. Resp.	Wavelength nm	IESNA Rel. Resp.	Wavelength nm	DIN Rel. Resp.	IESNA Rel. Resp.
		235,3	0,35	235		0,344
				236		0,362
				237		0,382
				238		0,404
				239		0,428
240	0,56			240	0,560	0,453
				241	0,580	0,480
				242	0,600	0,508
				243	0,620	0,537
		244,6	0,58	244	0,640	0,567
245	0,66			245	0,660	0,597
				246	0,680	0,627
				247	0,700	0,658
		248,2	0,70	248	0,720	0,689
				249	0,740	0,719
250	0,76			250	0,760	0,749
				251	0,780	0,778
				252	0,801	0,806
		253,7	0,85	253	0,821	0,833
				254	0,840	0,859
255	0,86			255	0,860	0,883
				256	0,880	0,906
		257,6	0,94	257	0,899	0,927
				258	0,917	0,945
				259	0,934	0,962
260	0,95			260	0,950	0,975
				261	0,964	0,986
				262	0,976	0,994
				263	0,987	0,999