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CIE

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

TECHNICAL REPORT

ULTRAVIOLET AIR DISINFECTION

CIE 155:2003

UDC: 612.014.481
628.356.15

Descriptor: Action of radiation
Air cleaners

THE INTERNATIONAL COMMISSION ON ILLUMINATION

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.

The objectives of the CIE are :

1. To provide an international forum for the discussion of all matters relating to the science, technology and art in the fields of light and lighting and for the interchange of information in these fields between countries.
2. To develop basic standards and procedures of metrology in the fields of light and lighting.
3. To provide guidance in the application of principles and procedures in the development of international and national standards in the fields of light and lighting.
4. To prepare and publish standards, reports and other publications concerned with all matters relating to the science, technology and art in the fields of light and lighting.
5. To maintain liaison and technical interaction with other international organisations concerned with matters related to the science, technology, standardisation and art in the fields of light and lighting.

The work of the CIE is carried on by seven Divisions each with about 20 Technical Committees. This work covers subjects ranging from fundamental matters to all types of lighting applications. The standards and technical reports developed by these international Divisions of the CIE are accepted throughout the world.
A plenary session is held every four years at which the work of the Divisions and Technical Committees is reviewed, reported and plans are made for the future. The CIE is recognised as the authority on all aspects of light and lighting. As such it occupies an important position among international organisations.

LA COMMISSION INTERNATIONALE DE L'ECLAIRAGE

La Commission Internationale de l'Eclairage (CIE) est une organisation qui se donne pour but la coopération internationale et l'échange d'informations entre les Pays membres sur toutes les questions relatives à l'art et à la science de l'éclairage. Elle est composée de Comités Nationaux représentant 38 pays plus un territoire géographique, et de 4 membres associés.

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1. De constituer un centre d'étude international pour toute matière relevant de la science, de la technologie et de l'art de la lumière et de l'éclairage et pour l'échange entre pays d'informations dans ces domaines.
2. D'élaborer des normes et des méthodes de base pour la métrologie dans les domaines de la lumière et de l'éclairage.
3. De donner des directives pour l'application des principes et des méthodes d'élaboration de normes internationales et nationales dans les domaines de la lumière et de l'éclairage.
4. De préparer et publier des normes, rapports et autres textes, concernant toutes matières relatives à la science, la technologie et l'art dans les domaines de la lumière et de l'éclairage.
5. De maintenir une liaison et une collaboration technique avec les autres organisations internationales concernées par des sujets relatifs à la science, la technologie, la normalisation et l'art dans les domaines de la lumière et de l'éclairage.

Les travaux de la CIE sont effectués par 7 Divisions, ayant chacune environ 20 Comités Techniques. Les sujets d'études s'étendent des questions fondamentales, à tous les types d'applications de l'éclairage. Les normes et les rapports techniques élaborés par ces Divisions Internationales de la CIE sont reconnus dans le monde entier.
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DIE INTERNATIONALE BELEUCHTUNGSKOMMISSION

Die Internationale Beleuchtungskommission (CIE) ist eine Organisation, die sich der internationalen Zusammenarbeit und dem Austausch von Informationen zwischen ihren Mitgliedsländern bezüglich der Kunst und Wissenschaft der Lichttechnik widmet. Die Mitgliedschaft besteht aus den Nationalen Komitees in 38 Ländern und einem geographischen Gebiet und aus 4 assoziierten Mitgliedern.

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2. Grundnormen und Verfahren der Meßtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
4. Normen, Berichte und andere Publikationen zu erstellen und zu veröffentlichen, die alle Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik betreffen.
5. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

Die Arbeit der CIE wird in 7 Divisionen, jede mit etwa 20 Technischen Komitees, geleistet. Diese Arbeit betrifft Gebiete mit grundlegendem Inhalt bis zu allen Arten der Lichtanwendung. Die Normen und Technischen Berichte, die von diesen international zusammengesetzten Divisionen ausgearbeitet werden, sind von der ganzen Welt anerkannt.
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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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.

Dieser Technische Bericht ist vom CIE Technischen Komitee 6-35 der Division 6 “Photobiologie und Photochemie” ausgearbeitet und vom Vorstand der Commission Internationale de l'Eclairage gebilligt worden. Das Dokument berichtet über den derzeitigen Stand des Wissens und Erfahrung in dem behandelten Gebiet von Licht und Beleuchtung; es ist zur Verwendung durch CIE-Mitglieder und durch andere Interessierte bestimmt. Es sollte jedoch beachtet werden, daß das Dokument eine Empfehlung und keine Vorschrift ist. Die neuesten CIE-Tagungsberichte oder das CIE NEWS sollten im Hinblick auf mögliche spätere Änderungen zu Rate gezogen werden.

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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”.

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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 20e 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 20e siècle jusqu'au début du 21e, 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 meilleures 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 mircoorganisms. 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 2×10^4 J/m^2; however, in general a dosage over 2×10^6 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.

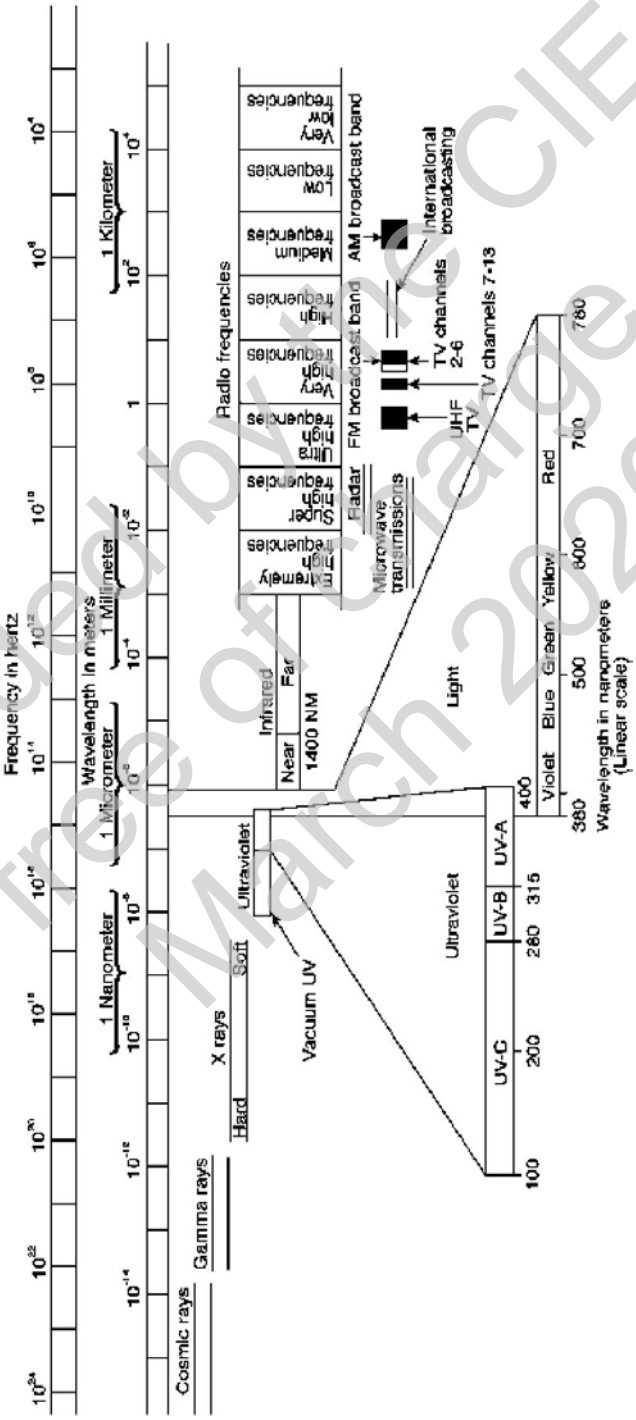

Fig. 1. Electromagnetic spectrum. Source: IESNA Lighting Handbook 9th Edition (IESNA, 2000b). Used with permission.

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 W = 1 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 $W/(m^2 \cdot sr)$.

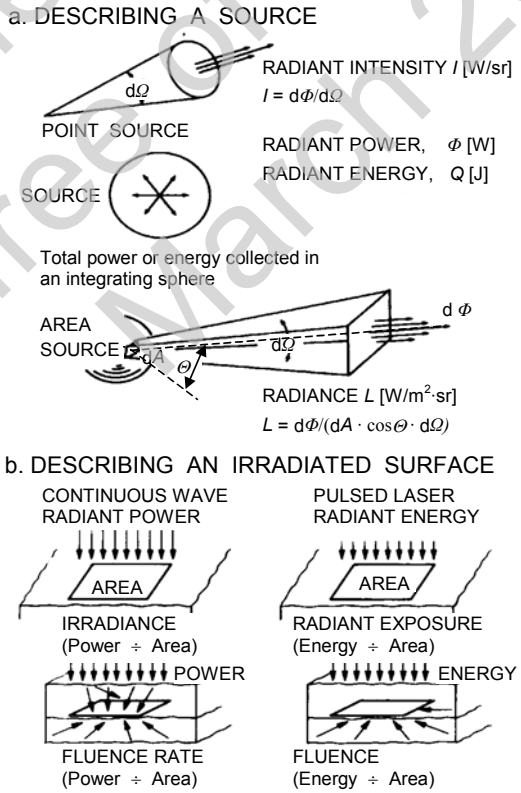

Fig. 2. Illustration of radiometric and fluence concepts. Source: CIE MORH (ICNIRP/CIE, 1998).

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·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·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 propotional 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 (10μW/cm^2) for 10 s is equivalent in killing power to 0,05 W/m^2 (5μW/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/1 s
irradiance (at a point of a surface) ILV 845-01-37 (CIE, 1987)	E_e	Quotient of the radiant flux dΦ_e incident on an element of the surface containing the point, by the area dA of that element.	W/m²	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/m²	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 incidente 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/m²	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/m²	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.

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

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 $\mu W/cm^2$ 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 $\mu W \cdot s/cm^2$ 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 ($erg \cdot mm^{-2}$) or ($erg \cdot cm^{-2}$). Today fluence is expressed in ($J \cdot m^{-2}$). The following relationship can be used to convert these units: $1\ J \cdot m^{-2} = 10\ erg \cdot mm^{-2} = 10^3\ erg \cdot cm^{-2}$

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 µm to 1,5 µm. 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 µm – 5 µm 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 µm in size, and that 5 µm particles were 80% screened. It was further determined that particles 5 µm 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, CO_2 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 Coblentz 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 distruction. 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.

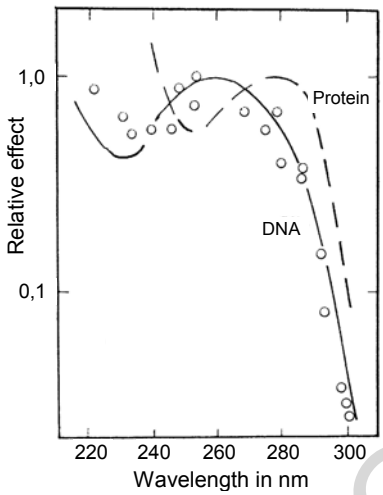

Fig. 3. Absorption spectra of DNA (solid line) and protein (dashed line) of UV. Cell death of unspecified bacteria (data points) follow DNA absorption, not protein absorption. Source: CIE MORH (ICNIRP/CIE, 1998).

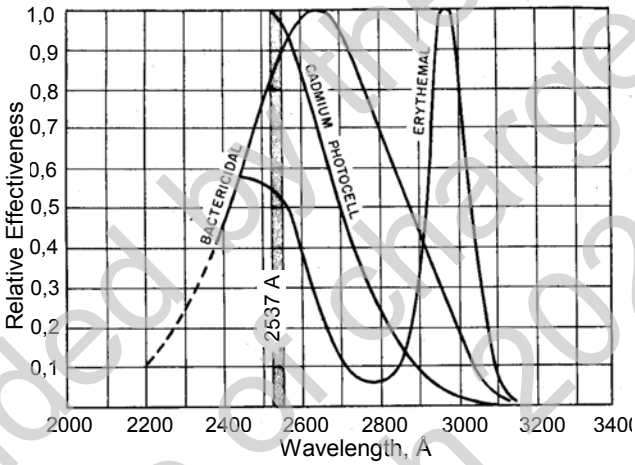

Fig. 4. Proposed CIE 1934 germicidal and erythemal action spectra. Source: CIE Compte Rendu (CIE, 1935).

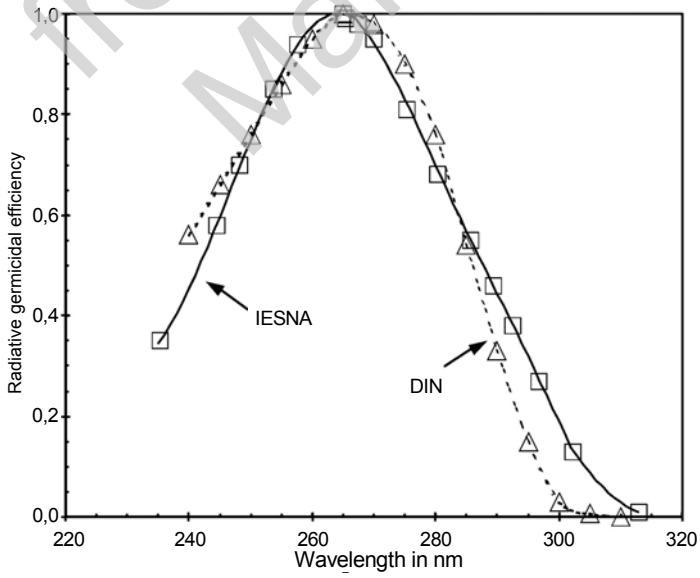

Fig. 5. Standard germicidal response curves (Data from Table 2).

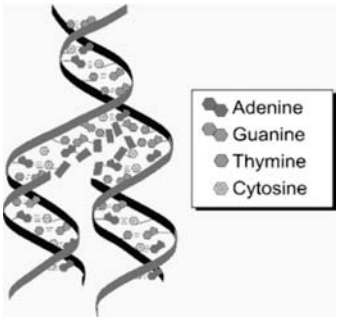

Fig. 6. DNA's two stranded double helix and constituent bases. Sufficient UV absorption breaks the hydrogen bonds between the bands rendering the microorganism harmless.

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

Defined Tabulated Values				Fitted Curves		
Wavelength nm	DIN Rel. Resp.	Wavelength nm	IESNA Rel. Resp.	Wavelength nm	DIN Rel. Resp.	IESNA Rel. Resp.
				264	0,995	1,000
265	1,00	265,0	1,00	265	1,000	1,000
		265,4	0,99	266	1,001	0,998
		267,5	0,98	267	1,000	0,990
				268	0,996	0,976
				269	0,989	0,960
270	0,98	270,0	0,95	270	0,980	0,942
				271	0,969	0,922
				272	0,955	0,901
				273	0,939	0,878
				274	0,921	0,855
275	0,90	275,3	0,81	275	0,900	0,830
				276	0,877	0,805
				277	0,852	0,779
				278	0,824	0,753
				279	0,794	0,726
280	0,76	280,4	0,68	280	0,760	0,700
				281	0,720	0,673
				282	0,677	0,647
				283	0,632	0,620
				284	0,586	0,594
285	0,54	285,7	0,55	285	0,540	0,569
				286	0,497	0,543
				287	0,454	0,518
				288	0,412	0,493
		289,4	0,46	289	0,370	0,468
290	0,33			290	0,330	0,444
				291	0,291	0,420
		292,5	0,38	292	0,253	0,396
				293	0,216	0,372
				294	0,182	0,345
295	0,15			295	0,150	0,319
		296,7	0,27	296	0,120	0,293
				297	0,093	0,268
				298	0,068	0,242
				299	0,047	0,216
300	0,03			300	0,030	0,191
				301	0,020	0,166
		302,2	0,13	302	0,013	0,138
				303	0,009	0,121
				304	0,007	0,104
305	0,006			305	0,006	0,088
				306	0,004	0,073
				307	0,003	0,060
				308	0,002	0,048
				309	0,001	0,038
310	0,001			310	0,001	0,029
				311		0,021
				312		0,014
		313,0	0,01	313		0,009

5.2 Photoreactivation (recovery and repair)

Recovery is the restoration of the microorganisms' ability to grow and form a colony after interaction with a physical agent, e.g., irradiation with UV (Kelner, 1949).

Photoreactivation has been broadly defined as a reduction in response of a biological system to UV irradiation, resulting from simultaneous exposure or post treatment exposure to non ionizing radiation (Harm, 1980). Some microorganisms (particularly bacteria) have a photorepair mechanism that dissociates the DNA photoproducts (thymine dimers) resulting from UVR exposure. This process is triggered by the absorption of visible light. The repair mechanism can be inhibited, but this requires a higher UV dose (Bolton, 1999). Near UV and visible light (330 nm to 480 nm) can result in up to 80% repair of UV radiation induced photochemical damage in many microorganisms (bacteria, fungi, viruses) as well as cells of animals and plants. This photoreactivation process may be due to an insufficient energy transfer of UV photons to the organism (Kelner, 1949; David et al., 1971; Dulbecco, 1955).

Because of the importance of mycobacteria (e.g., Mycobacterium tuberculosis) in the production of infectious disease, studies of the photoreactivation of these microorganisms after UV-C irradiation have been conducted to determine efficiency of inactivation by UV-C. David concluded that variations in the UV sensitivities within the mycobacterium family (including repair efficiency both under visible light and dark conditions) should not affect the practice of using ultraviolet irradiation in the control of airborne mycobacterial infections (David, 1973). It has long been known that biological repair from UV damage occurs for some microorganisms stored in the dark. Several mechanisms are grouped under the heading of dark recovery. For certain strains of E. coli, depending on the level of UV absorbed, recovery can reach 99% (Harm, 1980; Jagger, 1967; Schechmeister, 1991).

The potential UV susceptibility of microbes also includes structural, cellular and environmental factors that may alter the photochemical processes of UV energy absorption. Biological characteristics include bacterial growth stage, clumping, genome size and pigmentation as well as suspending medium and environmental conditions (Ko et al., 2000). Relative humidity is one of the more important environmental factors to control when designing UVGI applications. Beggs has developed a model to account for the sometimes rapid effects of photoreactivation (Beggs, 2002). His approach includes both single-hit and multi-hit models of inactivation. He proposes that researchers not only quantify the UV fluence rate but also the fluence rate of visible light.

5.3 Relative humidity

Experimental case studies in the 1970s showed that microorganisms exposed to UV were less susceptible to damage when the relative humidity (RH) was above 65-75% (Riley et al., 1976; Riley et al., 1972). Because short-wave UV-C is the least penetrating of all forms of UV, it is easily attenuated by glass, clothing and other matter. UV attenuation can also be due to increased microbe moisture content or coating which could possibly explain the experimental finding of greater survival of organisms exposed to UV at high levels of RH. These earlier bench experiments have recently been replicated to quantify a baseline of RH impact on organism UV susceptibility using commercially available germicidal lamps (Ko et al., 2000). Serratia marcensens and Bacillus Calmette-Guerin (BCG) aerosols with particle sizes of 1,1 μm – 4,7 μm were studied under different UV doses and RH levels. This particle size range is considered important because this is the size of TB bacteria (as well as other potential infectious microorganisms, i.e. anthrax spores), which have been shown to pass through the respiratory system's defense mechanism to reach the extremities of the lung's alveoli (air sacks) where infection takes place. BCG was found to be more resistant than S. marcensens, possibly due to the differences in their biological structure. Current UV susceptibility factors are lower than those Riley previously reported, possibly due to the isolate/strain used, particle size differences and different ranges of UV doses (Ko et al., 2000). These studies taken together indicate the important impact RH may have on the efficacy of UV-C air disinfection strategies. For example, higher doses of UV-C may be required in more humid climates to provide the equivalent protection of a drier environment. Studies are underway to extend the RH work through use of a room-scale chamber (Ko et al., 2002).

5.4 Microorganism UV susceptibility and UV dose

Given a sufficient absorbed dose of UV-C, organisms can be rendered harmless. To summarize, current data suggest that the incident radiant quantity required to inhibit the microorganism colony formation and photoreactivation environment depend upon:

- Microorganism structure and inherent ability to recover from damage induced by UVGI;
- Presence of sufficiently high radiant exposure over time;
- Degree of relative humidity.

5.5 Microorganism exponential decay (survival) curves

When considering UVGI exposure requirements for practical applications to limit airborne disease-transmission in indoor spaces, to kill or inactivate (make non viable) every single infectious particle by UVGI exposure is not realistic because individual particles, even from the same culture, show variable resistance to ambient conditions (First et al., 1999b). Therefore dose response curves are developed. Equation 1 is the solution to a differential equation developed on theoretical grounds. It represents the fractional survival of microorganisms exposed to UV. Figure 7 shows the resultant plot of Equation 1 for Mycobacterium tuberculosis exposed to 254 nm radiation in air (Riley et al., 1976).

$$\frac{N_s}{N_0} = e^{-K \cdot H_o} \qquad (1)$$

where N_0 = number of bacteria exposed;
N_s = number of bacteria surviving after an exposure to UVGI;
H_o = fluence, J/m^2;
K = decay rate constant, m^2/J (K is a measure of microbe susceptibility to UVGI).

While Equation 1 gives a straight line in semilogarithmic representation (see MTB example Figure 7), it is known that many microorganisms have shouldered survival (two stages of inactivation) that can occur with a slower decay at very long exposure times (Beggs, 2002; Cerf, 1977; Kowalski et al., 2000a).

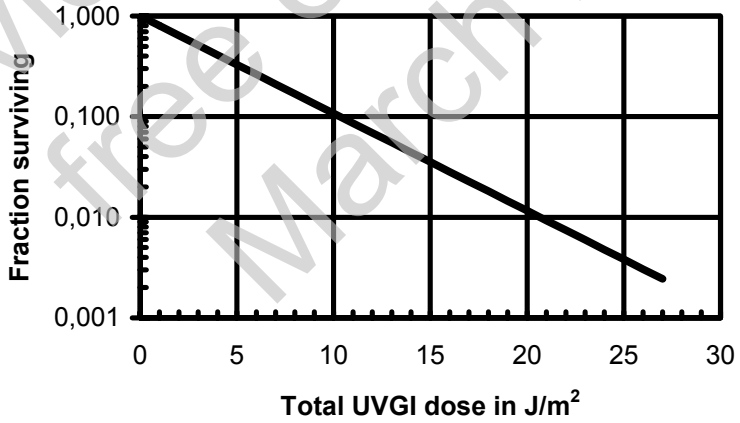

Fig. 7. Survival of tubercle bacilli exposed to various doses of 254 nm UV-C irradiation in air.

Fluence is the relevant “dose” for airborne microorganisms (bacteria, viruses and fungi) because they are equally susceptible to radiation coming from all directions, while for instance, for a flatter surface like human skin a cosine correction is necessary for radiation not perpendicular to the skin. The corresponding “dose” unit is radiant exposure (J/m^2).

Some microbes require a higher UVGI fluence than others to be killed or inactivated; for example, the tuberculosis causing - Mycobacterium tuberculosis (MTB) - requires a greater UVGI fluence than staphylococcus species (First et al., 1999a). A consideration of the total surface area of the microbe (in cm^2) exposed to the radiation makes it possible to

estimate the total energy absorbed by the microorganism in microjoules (μJ), a measure of total UV dose, when the average irradiance is known. The calculation of the energy absorbed by a microorganism is a difficult task because the absorption coefficients and the homogeneity of absorption in the particle are not well known. Therefore the incident radiation is almost always used as the measure of "dose" for microorganisms and not the absorbed energy.

Germicidal fluence, as stated above, is the total amount of energy to which an airborne microorganism is exposed, expressed as the product of the UVGI fluence rate on the microbe (usually in units of watts per square meter [W/m^2] and time).

The germicidal weighted fluence $H_{o,g}$ is defined by:

$$H_{o,g} = \int_{200}^{400} s_g(\lambda) \cdot H_{o,\lambda}(\lambda) \cdot d\lambda \qquad (2)$$

where $s_g(\lambda)$ is the relative spectral sensitivity of the microorganism. If the normalisation of the function $s_g(\lambda)$ is performed in such a way that $s_g(254) = 1$ the value of $H_{o,g}$ gives the same inactivation as a fluence H_o of radiation at 254 nm with the same value.

$H_{o,\lambda}(\lambda)$ is the spectral fluence (the spectrum of the radiation) in J/(m^{2}nm).

For practical reasons the integration may be replaced by summation:

$$H_{o,g} = \sum_{200}^{400} s_g(\lambda) \cdot H_{o,\lambda}(\lambda) \cdot \Delta\lambda \qquad (3)$$

5.6 Decay rate constant, *K*

Results from various studies conducted on many microorganisms to determine the fractional survival of exposed cell populations vs. a carefully measured dose of UVGI give the decay constant as a measure of the microorganism's susceptibility. While Kethley and other investigators have used the symbol *Z* to define this decay rate constant (Kethley, 1978), the symbol, *K*, will be used for the purposes of this report and defined as the negative of the slope of resulting logarithmic survival curves. *K* is a measure of the intrinsic susceptibility (sensitivity) of the microorganism to UV exposure, where the larger the numerical *K* value, the greater the sensitivity (or more easily killed), the smaller the *K* value, the more resistant to UV killing (inactivation). *K* can be calculated from Equation 1 as follows:

$$K = \frac{-\ln \frac{N_s}{N_0}}{H_o} \qquad (4)$$

where K = decay rate constant, m^2/J (*K* is a measure of microbe susceptibility to UVGI)
ln = natural logarithm (to the base e);
N_s = number of bacteria surviving after an exposure to UVGI;
N_o = number of bacteria exposed;
H_o = fluence, J/m^2.

A particular lethal dose (LD_{90} is the dose for 10% survival) can be calculated by knowing the *K* value for a specific microorganism by transforming Equation 4 as follows:

$$H_o = LD_{90} = \frac{-\ln \frac{N_s}{N_0}}{K} \qquad (5)$$

These mathematical relationships were used to derive Table 3 of microorganism susceptibility to UV.

5.7 Table of microorganism susceptibility

For the CIE Aydinli and Krochmann (Aydinli et al., 1985) have compiled several studies of the doses for 10% survival under UV-C 254 nm radiation and microorganism susceptibility factor

K. This compilation should be considered an approximation of effectiveness (see heading note in Table 3).

Table 3. Actinic radiant exposure *H* at 253, 7 nm necessary to inhibit colony formation in 90% of organisms (10% survival) [Tabular information adapted from Aydinli and Krochmann (Aydinli et al., 1985) and Kowalski (Kowalski et al., 2000a). Used with permission.]

Note: Although data from both air and surface (plate) exposures are intermixed in this table, the LD_{90} doses for each cannot be compared directly. It is generally much easier to inactivate microbes in the air than on surfaces. In both air and on surfaces the LD_{90} depends on the exact conditions of each experiment. Susceptibility differences in air between species may reflect differences in the conditions of the study as well as differences proper to the species.

Microorganism	(H_o) Radiant Exposure $J \cdot m^{-2}$	(K) Decay Rate Constant $m^2 \cdot J^{-1}$	Reference	Type	Test Medium
Bacillus anthracis(vegetative)	45,2	0,05	Sharp, 1938	Bacteria	Air
Bacillus anthracis (spores)		0,0031	Knudson, 1986	Bacteria	Plates
S. enteritidis	40,0	0,058	Dreyer et al., 1936	Bacteria	Plates
B. megatherium sp. (veg.)	37,5	0,061	Hercik, 1937	Bacteria	Plates
B. megatherium sp. (spores)	28,0	0,082	Hercik, 1937	Bacteria	Plates
B. paratyphosus	32,0	0,072	Dreyer et al., 1936	Bacteria	Plates
B. subtilis (mixed)	71,0	0,032	Rentschler, 1941	Bacteria	Air
	60,0	0,038	Koller, 1939	Bacteria	Air
B. subtilis spores	120,0	0,019	Rentschler, 1941	Bacteria	Air
Corynebacterium diptheriae	34,0	0,068	Sharp, 1938	Bacteria	Air
		0,070	Sharp, 1939	Bacteria	Plates
Eberthella typhosa	21,4	0,108	Sharp, 1938	Bacteria	Air
Micrococcus candidus	60,5	0,038	Ehrismann et al., 1932	Bacteria	Plates
Micrococcus piltonensis	81,0	0,028	Rentschler, 1941	Bacteria	Air
Micrococcus sphaeroides	100,0	0,023	Rentschler, 1941	Bacteria	Air
Neisseria catarrhalis	44,0	0,052	Rentschler, 1941	Bacteria	Air
Phytomonas tumefaciens	44,0	0,052	Rentschler, 1941	Bacteria	Air
Proteus vulgaris	27,0	0,085	Rentschler, 1941	Bacteria	Air
Pseudomonas aeruginosa		0,238	Collins, 1971	Bacteria	Air
		0,572	Sharp, 1940	Bacteria	Air
	55,0	0,042	Ehrismann et al., 1932	Bacteria	Plates
Pseudomonas florescens	35,0	0,066	Ehrismann et al., 1932	Bacteria	Plates
S. typhimurium	80,0	0,029	Dreyer et al., 1936	Bacteria	Plates
Sarcina lutea	197,0	0,012	Rentschler, 1941	Bacteria	Air
Serratia marcesens	24,2	0,095	Rentschler, 1941	Bacteria	Air
	22,0	0,105	Sharp, 1938	Bacteria	Air
	8,3	0,277	Ehrismann et al., 1932	Bacteria	Plates
		0,221	Collins, 1971	Bacteria	Air
		0,214	Riley et al., 1976	Bacteria	Air
		0,445	Sharp, 1940	Bacteria	Air
Dysentery bacilli	22,0	0,105	Dreyer et al., 1936	Bacteria	Plates
Shigella paradysenteriae	16,8	0,137	Sharp, 1938	Bacteria	Air
Spirillum rubrum	44,0	0,052	Rentschler, 1941	Bacteria	Air

Microorganism	(H_o) Radiant Exposure $J \cdot m^{-2}$	(K) Decay Rate Constant $m^2 \cdot J^{-1}$	Reference	Type	Test Medium
Staphylococcus albus	18,4	0,125	Sharp, 1938	Bacteria	Air
	33,0	0,070	Rentschler, 1941	Bacteria	Air
	18,4	0,125	Rentschler, 1941	Bacteria	Air
Staphylococcus aureus	21,8	0,106	Gates, 1929	Bacteria	Plates
	49,5	0,047	Ehrismann et al., 1932	Bacteria	Plates
		0,089	Sharp, 1939	Bacteria	Plates
		0,348	Sharp, 1940	Bacteria	Air
		0,042	Abshire, 1981	Bacteria	Plates
		0,960	Luckiesh, 1946	Bacteria	Air
Streptococcus haemolyticus	26,0	0,089	Sharp, 1938 and 1939	Bacteria	Air/Plate
	21,6	0,107	Sharp, 1938	Bacteria	Air
Streptococcus lactis	61,5	0,037	Rentschler, 1941	Bacteria	Air
Streptococcus viridians	20,0	0,115	Sharp, 1938	Bacteria	Air
Clostridium tetani	49,0	0,047	Sharp, 1939	Bacteria	Plates
Streptococcus pyogenes	21,6	0,107	Sharp, 1939	Bacteria	Plates
		0,616	Lidwell, 1960	Bacteria	Plates
		0,107	Misterlich et al., 1984	Bacteria	Air
Streptococcus salivarius	20,0	0,115	Sharp, 1939	Bacteria	Plates
Streptococcus albus	18,4	0,125	Sharp, 1939	Bacteria	Plates
B. prodigiosus	8,3	0,329	Ehrismann et al., 1932	Bacteria	Plates
B. pyocyaneus	55,0	0,052	Ehrismann et al., 1932	Bacteria	Plates
Mycobacterium tuberculosis (Tubercle bacilli)		0,099	David, 1973	Bacteria	Air
		0,472	Riley et al., 1976	Bacteria	Air
		0,213	Collins, 1971	Bacteria	Air
	100,0	0,023	Philips Lighting, 1972	Bacteria	Plates
Mycobacterium kansasii		0,036	David, 1973	Bacteria	Air
Mycobacterium avium-intra.		0,041	David, 1973	Bacteria	Air
Escheria coli		0,093	Sharp, 1939	Bacteria	Plates
		0,376	Sharp, 1940	Bacteria	Air
Haemophilus influenzae		0,060	Mongold, 1992	Bacteria	Plates
Adenovirus		0,055	Jensen, 1964	Virus	Air
		0,0047	Rainbow et al., 1973	Virus	Plates
Vaccinia		0,153	Jensen, 1964	Virus	Air
Vaccina		0,155	Galasso et al., 1965	Virus	Plates
Coxsackievirus		0,111	Jensen, 1964	Virus	Air
Influenza A		0,119	Jensen, 1964	Virus	Air
Cryptococcus neoformans		0,010	Wang et al., 1994	Fungal spores	Plates
Fusarium oxysporum		0,011	Asthana et al., 1992	Fungal spores	Plates
Fusarium solani		0,0071	Asthana et al., 1992	Fungal spores	Plates
Penicillium italicum		0,013	Asthana et al., 1992	Fungal spores	Plates
Penicillium digitatum		0,0072	Asthana et al., 1992	Fungal spores	Plates
Rhizopus nigricans spores		0,0086	Luckiesh, 1946	Fungal spores	Air

Microorganism	(H_o) Radiant Exposure $J \cdot m^{-2}$	(K) Decay Rate Constant $m^2 \cdot J^{-1}$	Reference	Type	Test Medium
Cladosporium herbarum		0,0037	Luckiesh, 1946	Fungal spores	Air
Scopulariopsis brevicaulis		0,0034	Luckiesh, 1946	Fungal spores	Air
Mucor mucedo		0,0040	Luckiesh, 1946	Fungal spores	Air
Penicillium chrysogenum		0,0043	Luckiesh, 1946	Fungal spores	Air
Aspergillus amstelodami		0,0034	Luckiesh, 1946	Fungal spores	Air
Fusarium oxysporum		0,011	Asthana et al., 1992	Fungal spores	Plates
Fusarium solani		0,0071	Asthana et al., 1992	Fungal spores	Plates
Penicillium italicum		0,013	Asthana et al., 1992	Fungal spores	Plates
Penicillium digitatum		0,0072	Asthana et al., 1992	Fungal spores	Plates

5.8 Development of algorithms of UVGI air disinfection potential

Riley pointed out that the significance of the decay rate constant, *K*, is best understood in analogy with ventilation where fresh air entering the room removes contaminated air in a logarithmic fashion. When the volume of entering fresh air (and return air leaving) a room is equal to the volume of the room, one air change (AC) occurs, with 63% of the contaminated air removed. This leaves 37% contaminated air remaining. Germicidal irradiation reduces the concentration of viable airborne microbes in a similar logarithmic manner, for example, if the reduction in airborne viable bacteria due to UV alone during any given period was found by measurement to be 63%, the N_s/N_0 ratio would be 0,37 and the negative logarithm would be 1,0 (Kundsin, 1988a). Riley developed the concept of equivalent air changes per hour (ACH_{eq}) through a series of room-scale experiments. ACH_{eq} is defined as the number of theoretical room air changes in a well-mixed room that would be required to reduce the number of viable airborne bacteria to the same degree as the UV irradiation alone. Experiments were conducted where microbes were aerosolized into the air of a closed room with a floor area of 18,6 m^2 and a ceiling height of 3,7 m. The rate of disappearance of viable organisms naturally and from fresh air infiltration was determined. He then repeated the experiment with the germicidal lamp turned on. The UVGI fixture used allowed unobstructed irradiation above 2,3 m but cut off germicidal irradiation below this level. Upper room UVGI of occupied rooms is placed above the heads of occupants to eliminate exposure that could cause irritation to eyes and skin. His results (Figure 8) show the potential air cleansing effect of upper room UV irradiation where the effective contaminant removal is increased by 10 ACH_{eq} (Riley et al., 1976).

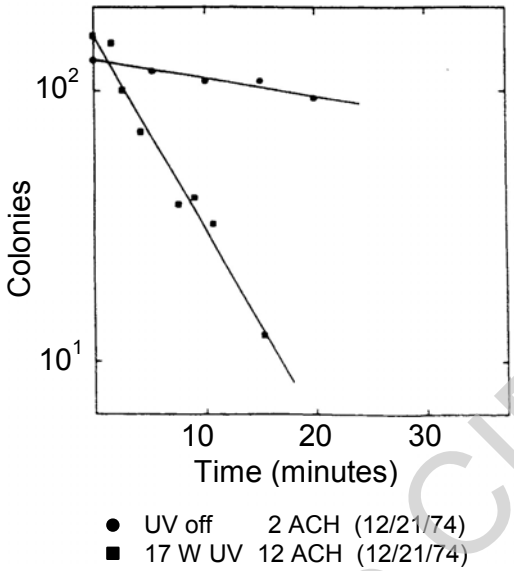

Fig. 8. Disappearance of aerosolized bacillus Calmette-Guérin (BCG) from room air with and without upper room ultraviolet (UVGI) irradiation using one suspended fixture with one 17 W lamp, ACH=air changes/hour. Y-axis = viable colonies remaining in air. X-axis = duration of exposure to UVGI. Adapted from Riley (Riley et al., 1976) and used with permission of Journal of the American Thoracic Society.

Riley theorized that using the same fluence of UV, the rate of killing organisms in the upper air should be directly related to the decay constant, *K*, with ACH_{eq} in the lower room air being less correlated due to variations in air mixing between the upper and lower room. He conducted a series of room experiments to test this hypothesis using a series of microbial aerosols exposed under equivalent conditions to UVGI in the upper room. Riley converted the room exposure results into ACH_{eq} and plotted the results (Figure 9) one for one to the same microorganism exposed to UV in a small exposure chamber. These two methods give an indication of the quantitative results of what might be achieved from overhead UVGI.

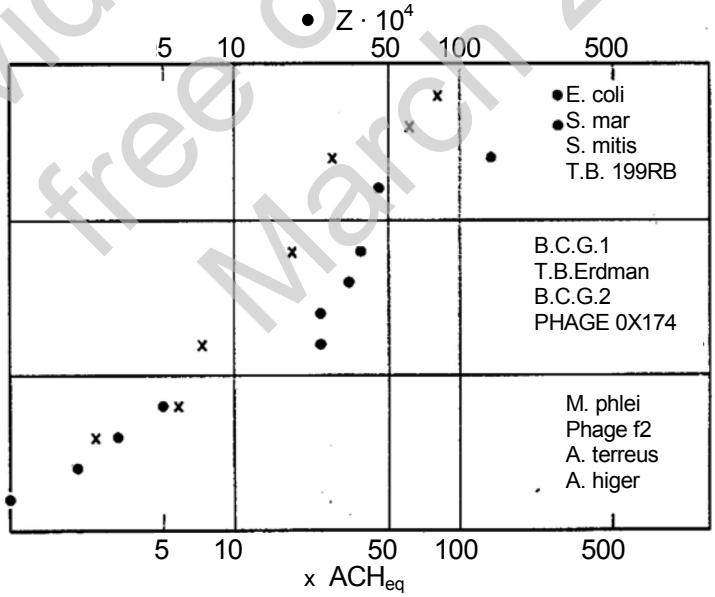

Fig. 9. Relative susceptibility of various organisms to ultraviolet germicidal irradiation determined by two methods: inactivation in a small *exposure chamber* (circles, *Z* units x 10^4 (*Z* is also the same as the decay rate constant, *K*)), and inactivation of aerosolized organisms by overhead irradiation, as determined in a room 18,6 m^2 with a 30 W UV lamp with an overhead UV (x's, ACH_{eq}). Adapted from Riley (Riley, 1988) and used with permission of Journal of the American Thoracic Society.

Upper-room UVGI holds the promise of destroying airborne microbes when they rise and enter the irradiated zone below the ceiling. Thus, every time room air currents bring 63% of the airborne microbes into the UVGI beam long enough to induce a lethal radiation dose this is equivalent to one room air change in terms of germicidal effect. When it can be shown that 99% of airborne infectious particles are killed by UVGI alone in 15 minutes, it may be said that UVGI is providing the germicidal equivalent of 18 ACH. At the same time, the normal room mechanical ventilation system will purge contamination by dilution and displacement in the usual way, and the effects will be additive. This means that the room ventilation normally used to provide heating, cooling, and elimination of stagnant air can be designed for yet another service, namely to increase upflow and thereby increase the rapid destruction of infectious particles emitted into the room air.

By using paired room experiments that measure the decay of identified viable airborne bacteria over time when the UVGI fixtures are on and off, it becomes feasible to use the on-off number ratio, with *K*-values such as those shown in Table 3, to solve Equation 5 for average UVGI fluence (H_0) in the room. In as much as the numbers derived from the paired experiments represent (1) the reduction in viable bacteria by the known air exchange rate alone (UVGI off) and (2) the reduction by air exchange plus radiation (UVGI on), it is possible to express the reduction caused by radiation alone as an equivalent air exchange rate, thereby highlighting in terms familiar to HVAC specialists the savings obtainable when using UVGI to purge room air of viable bacteria rather than using an increased number of actual room air changes. To illustrate this point Equation 1 can be restated in the following form:

$$-\ln\frac{N_S}{N_0} = K \cdot H_o \qquad (6)$$

Because the process of air passing steadily from the lower contaminated zone to the upper UVGI purifying zone, where some fraction of the entrained bacteria are killed or inactivated, follows the same logarithmic decay function as occurs by ventilation air changes alone, Equation 3 can be amplified as follows:

$$AC_{eq} = -\ln\frac{N_S}{N_0} = K \cdot H_o \qquad (7)$$

For example, if the reduction in airborne viable bacteria due to UV alone during any given period was found by measurement to be 63%, the N_s/N_0 ratio would be 0,37 and the negative logarithm would be 1,0, indicating that the UVGI system increased bacterial purging by the same amount that would have been observed had the ventilation rate been increased by one air change alone. Had the reduction due to UVGI alone been 95%, the negative logarithm of 0,05, namely three, indicates that this effect is the same as increasing the air rate by three changes. If the UVGI reduction of 95% occurred during 15 minutes, the air exchange rate would be equivalent to $(3 \times 4) = 12$ AC. The ability to express the bacteria-destroying effect of upper-room UVGI as equivalent air changes makes it possible to compare the purchase, installation, and operating costs of upper-room UVGI with an equivalent amount of heating, ventilating, and air conditioning (HVAC) capacity to provide the same level of air sanitation.

Using aerosolized surrogate mycobacteria exposed to carefully controlled UVGI doses, bench experiments have been extrapolated to estimate that 63% of airborne tuberculosis bacteria are inactivated (the germicidal equivalent of one room air change) when exposed for 24 seconds in an upper room irradiated zone with average germicidal effective irradiance of 10 μW/cm^2. Therefore 99% will be killed in 2 minutes (equivalent of five room air changes) (Riley et al., 1976). This means that the upper-room irradiation zone is being cleared of bacteria at a rate equivalent to 150 ACH (an impractical ventilation rate), assuming perfect mixing of residual microbes and perfect mixing of in-coming air with residual air. When the volume of air in the upper, irradiated portion of the room is approximately one-fifth that of the entire room, the time required to produce the same degree of air disinfection in the lower, occupied space is approximately five times longer, assuming perfect mixing of the air between the upper and lower-room. The real rate of air disinfection in the lower-room is dependent on the rate of vertical air mixing between the upper and lower-room, but this is often substantial due to the large cross-sectional area of a room. An optimal upper-room UV installation, therefore, has the potential of producing the germicidal equivalent of 20 ACH or

more in the occupied lower-room. In addition to the mixing produced by normal mechanical ventilation systems, vertical air movement can be enhanced with the aid of fans, as well as by adding warmth to the lower part of the room or cold air to the upper part, depending on seasonal requirements (Riley and Permutt, 1971).

5.9 Efficacy of UVR

Studies of real world application

In his original overlapping research objectives Wells sought to demonstrate the ability of UVGI to limit the spread of airborne infection in individual rooms; to trace infection in the community; and, ultimately to control the spread of airborne infection in the community (Wells, 1955). He was able unequivocally to achieve his first two objectives; however, the control of community airborne infection was limited. In the 1940s Wells and colleagues were able to show that the spread of measles among school children could be interrupted by upper room UV air irradiation (Wells et al., 1942). Others who tried to repeat his work were not as successful, primarily it is thought because children shared common air on school buses, which were not protected by UVGI (MRC, 1954). Riley sought to limit transmission of tuberculosis during a two-year study in an active TB ward. He not only proved airborne TB transmission but also was able to show the protective effect of UVGI for a colony of guinea pigs housed in a specialized chamber. Two different animal chambers were developed which received exhausted air from a tuberculosis ward through the chambers. One chamber received UVGI irradiated air while the other did not. Over the two-year course of the study the guinea pigs breathing irradiated air did not become infected with tuberculosis while those breathing untreated air did become infected (Riley et al., 1959; Riley et al., 1957). Macher studied the effectiveness of UVGI in a clinic waiting room but did not show UVGI as effective possibly due to overwhelming natural (open windows) and mechanical ventilation (Macher, 1993). This study indicates the importance of understanding the ventilation patterns in a space when placing UVGI. Kethley's studies in a model patient room confirmed the importance of the impact on overall effective air cleansing of the placement of UVGI in combination with room ventilation (Kethley, 1978). If airborne organisms are limited in exposure to UVGI due to the rapid circulation and clearance by ventilation, UVGI may not have the time needed to inactivate the microorganism. There are ongoing initiatives to model these impacts using an advanced computer technique known as computational fluid dynamics (CFD) (Memarzadeh, 2000; Kowalski et al., 2000b). An epidemiological field trial as described below is the most recent attempt to determine UVGI efficacy.

Use of UVGI in operating room suites has proven efficacious in reducing the number of post-operative infections. UVGI units have been used in the Duke University Medical Center's orthopaedic operating rooms (OR) since 1934. Prior to installation of UVGI in the OR, the postoperative wound infection rate was 10% of the cases. This rate subsequently dropped to less than 0,5% in operating areas equipped with UVGI and ventilation (Goldner et al., 1980). Kundsin reported a 50% reduction in wound infection of the orthopedic service covered by direct UVGI versus similar service areas in the same hospital with no UVGI (Kundsin, 1988b).

Epidemiological studies: Tuberculosis ultraviolet shelter study

Prior to widespread recognition of the resurgence of TB in the United States, Brickner, a physician in New York City, noticed many new cases of TB in a large men's homeless shelter. He wondered why no UV fixtures were being hung. He recalled that, as an intern in the 1950s, these were in common use for air sanitation. His inquiries showed that, although regulators believed that UV science was sound, there remained scepticism about efficacy in application. This led to the Tuberculosis Ultraviolet Shelter Study (TUSS).

An epidemiological field trial of UVGI efficacy, TUSS is an ongoing multi-year, multi-center, placebo controlled, double-blinded crossover design (Brickner et al., 2000). Begun in 1997 and now collecting data in 4 USA cities, in 12 different buildings (with ventilation ranging from natural to modern construction), TUSS leadership hopes to establish whether or not UVGI is efficacious for control of airborne disease transmission. Over 1 200 UVGI fixtures are installed covering ~70 000 m^3. Homeless shelters in cities with high rates of tuberculosis were

chosen by surveying physical characteristics, as well as space utilization, in order to plan an effective placement of upper room UVGI equipment while maintaining safety of room occupants. The chosen shelters generally have ceiling heights of 2,3 m (8 ft) or greater. Sites with lower ceilings use self-enclosed UV-fan units (mounted on walls or free standing on the floor). These UV-fan units contain dust filters and UVGI lamps but no HEPA filters, so that the true impact of UVGI and ventilation alone can be determined.

This work is now being extended to determine the role of UVGI in deterring bioterrorism countermeasures by applying lessons learned from extensive application of UVGI in high-risk settings.

6. APPLICATION OF ULTRAVIOLET GERMICIDAL IRRADIATION (UVGI)

6.1 Criteria to determine UVGI placement

Previous sections have discussed the various degrees of susceptibility of microorganisms to inactivation. In considering the use of UVGI to control transmission of airborne infectious microbes, consideration must be given to the source of the contaminant. Once the contaminant source is identified appropriate controls can be applied. For example, in normal human-to-human transmission of infectious particles, as in a healthcare setting, UVGI is placed in waiting rooms, patient rooms, and special treatment areas. For TB, in many cases it is the undiagnosed person who is silently transmitting infectious particles by talking and coughing. As in other engineering applications, a predetermined level of risk needs to be set in order to provide coverage where the potential of infectious transmission might be greatest. This will help determine how UVGI will be strategically placed, and at what level of inactivation to achieve the sought kill rate.

6.2 Models to assess the potential of transmission of infectious disease

Mathematical models have been developed to help determine the potential of infection in normal human transmission of infectious disease. A classic model is that of Wells-Riley, developed to estimate the probability of airborne transmission of an infectious agent indoors:

$$P = \frac{D}{S} = 1 - \exp\left[-\frac{I \cdot p \cdot q \cdot t}{Q}\right] \tag{8}$$

where P is the probability of infection for susceptibles, D is the number of disease cases, S is the number of susceptibles, I is the number of infectors, p is the breathing rate per person (m^3/s), q is the quantum generation rate by an infected person (quanta/s), t is the total time (s), and Q is the outdoor air supply rate (m^3/s). Investigators are refining these models and using them to assess the impact of various environmental control strategies (Ko et al., 2001; Nicas, 1996).

6.3 Whole building coverage

Because of the unknown infectious case, high-risk institutions might follow Riley's suggestion of whole building irradiation in combination with ventilation and filtration strategies (Riley, 1994). Cole has studied infectious aerosols in healthcare settings to provide a basis for evaluating these engineering strategies (Cole et al., 1998). Further research is needed to realize the full benefit of a systems integrated approach.

6.4 Upper-room UVGI air disinfection

The goal of upper room UVGI is to lower concentrations of airborne organisms in the breathing zone and recirculated air and thus to control the spread of infection to room and building occupants. The effectiveness of UV air disinfection depends upon the following factors: (1) germicidal fluence; (2) susceptibility of the microbe to UVGI; and (3) humidity (a minor factor). For upper-room UV air disinfection an essential factor is air turnover rate between the upper and lower room, which defines the duration of a microbe's exposure to the UV irradiation. The fluence (dose) needed to kill a microorganism is the time integral of the fluence rate $E_{e,o}$ at a given point over a given duration Δt in J/m^2.

All these factors require careful planning of fixture placement of UVGI in relation to room geometry and ventilation mode for maximum microbial destruction efficiency. Planning a UVGI installation to optimize efficacy and safety faces practical limits. To retrofit an existing building, floor to ceiling heights and existing ventilation (natural and/or mechanical) can limit options. Sometimes ceilings can be raised and supplemental fans installed. If the floor to ceiling heights is less than 2,3 m, concerns for eye exposure to UV-C increase. Also, if vertical air circulation is insufficient to elevate infectious particles into the irradiation zone, efficacy diminishes. New construction should integrate these requirements in the beginning of the building design process.

Energy effectiveness (of UVGI with normal ventilation vs. ventilation alone) can be demonstrated and quantified by calculating the number of additional air changes needed to produce the same clearance rate of viable microbes irradiated with UVGI. For a room normally ventilated by 6 ACH, an installed upper-room UVGI system can achieve 10 to 20 additional ACH equivalents.

6.5 Upper-room UVGI system planning, installation and commissioning

Riley concluded that building occupants could be significantly yet incompletely protected (99,97% kill) from respiratory infection using UVGI air disinfection provided that (1) exposure to infection occurs predominately within the building; (2) the ceilings are high enough to permit overhead irradiation with UVGI; (3) the relative humidity in the building is less than 70%; and (4) the rate at which airborne pathogens are produced is not overwhelming. His principles of UVGI air disinfection are the current basis for UVGI placement (Kundsin, 1988a). While Riley based his conclusions on TB and its surrogates, each upper room UVGI application would need to develop a level of killing based on risk assessment from analyzing the range of microorganisms to be controlled. This would be the beginning of design criteria regarding fluence needed to inactivate, for example, the most resistant species.

To plan a UVGI installation, consulting engineers/architects obtain building plans (or generate them on the spot by physically measuring the spaces and inputting the results into a computer aid design program). A physical survey of the facility is conducted to determine room occupancy usage. Riley's research indicated the number of UVGI fixtures required could be estimated for large rooms with ceilings heights of 4 m to 4,7 m based on the crowding conditions. One 30 W UVGI lamp would be needed for every 7 persons or for other spaces it would be one 30 W UVGI lamp per every 18,6 m^2. For large rooms in excess of 4,7 m, Riley recommended calculating the number of fixtures based on H_o since the volume of upper room air to be treated would be greater (Riley, 1988). Congregate areas are of primary interest for coverage. The engineer determines final fixture placement and equipment specifications to be used by the electrical contractor for installation. All UVGI equipment must meet uniform acceptance criteria through a submission process before consideration of purchase. The consulting engineer tests the range of effectiveness of the UVGI equipment to determine where it will be most effective in the UVGI plan.

Upper room UVGI fixtures are louvered to prevent direct radiation into the lower part of the room. Some fraction of the UV radiation directed into the upper room will be scattered from the upper room surfaces into the lower room area. This scattered radiation commonly will be insignificant both from consideration of germicidal action and of exposure hazards because almost all paints and other room surface finishes have very low reflectance at 254 nm (typically on the order of 5 percent). However, metallic surfaces, unfinished plaster, and some ceiling tiles can have appreciable UV reflectance. UV reflectance data is not often available for architectural materials and finishes. Unless such information is available to confirm that scattered UV will not be a hazard, measurements should be made on the final installation to confirm that unsafe UV exposure levels do not exist. Future work is expected to reduce the uncertainties in this aspect of the system design.

6.6 Upper-room UVGI guidelines and standards

Interim guidelines for the application of UVGI equipment have been developed (First et al., 1999b). International and USA national lighting organizations are working to create standards for characterizing UVGI equipment by independent testing laboratories. Additionally, they are working to develop state-of-the art reports on UVGI application. Ultraviolet air disinfection is

accepted as a supplement to ventilation and filtration by the United States Centers for Disease Control and Prevention (CDC) and the Medical Research Council (MRC) of South Africa (Coker et al., 2001). CDC describes three forms of environmental control for TB transmission: (1) dilution with outside air; (2) HEPA filtration; and (3) ultraviolet germicidal irradiation (CDC, 1994).

6.7 Guidance for UVGI in resource-limited countries

In some climates or in certain high-risk areas of a facility, use of natural and mechanical ventilation may not be feasible. In these situations, ultraviolet germicidal irradiation (UVGI) or portable HEPA filter units may provide a less expensive alternative to more expensive environmental measures that require structural alterations of a facility. These measures may be particularly useful for protecting healthcare workers (HCW) in TB wards, TB clinic waiting areas or inpatient areas such as television or recreation rooms where TB patients congregate. Studies show that M. tuberculosis is killed if the organisms are exposed sufficiently to UVGI. The major concerns about UVGI have been adverse reactions (e.g., acute and chronic cutaneous and ocular changes) in healthcare workers and patients if the UVGI is not installed and maintained properly. If UVGI is to be used, guidelines provided in references Coker et al., 2001 and WHO/CDS, 1999 as well as manufacturer's instructions regarding installation, cleaning, maintenance, and ongoing monitoring should be carefully consulted. UVGI may be applied in several forms:

- if healthcare workers and patients are in the room, continuous upper air irradiation can be used in which shielding placed below the UVGI sources prevents exposure to occupants;
- portable UVGI floor, wall or ceiling units also may be used;
- an additional more expensive option involves the use of UVGI in combination with a closed mechanical system.

Continuous upper air irradiation is the most appropriate method in most resource-limited countries. The advantage of this technology is that the upper air is continuously irradiated; thus, it provides some protection to the HCW while the infectious patient is in the room. This requires good air mixing to be effective. However, structural features such as low ceiling height may limit the feasibility and usefulness of UVGI. If portable UVGI floor, wall or ceiling units are used, attention should be paid to placement, since corners of the room may not be treated. The quality of UVGI lamps is very important. Usually a good lamp will last 5 000 to 10 000 hours (7-14 months). After that, the irradiance drops off rapidly. Responsibility should be assigned to ensure the lamps are cleaned and monitored properly (WHO/CDS, 1999).

6.8 Commissioning, monitoring, and maintenance of upper-room UVGI systems

Field safety measurements of UV in the occupied zone need to be taken with a UV meter calibrated to detect 253,7 nm radiation (Figure 10). There is a general lack of commercial testing of UVGI fixture output. Standardized methods for characterizing UVGI fixture output are being developed to be used as a basis for consensus testing procedures of germicidal equipment (Dumyahn et al., 1999; Ryer, 1992; Stead, 1984).

At present, where UVGI systems are used as a part of a hospital’s infection control plan, regular monitoring is needed in order to determine how frequently lamps and fixtures need to be cleaned to maintain output (Figure 11). Annual group re-lamping is recommended with spot replacement as necessary. See germicidal lamp section for further maintenance issues.

Fig. 10. Measuring UVGI fixture output to ensure effective level of UVGI using a radiometer fitted with a 254 nm sensor. Source: TUSS Saint Vincent's Hospital, Manhattan, NY. Used with permission.

Fig.11. Cleaning and annual relamping UVGI pendant fixture. Source: TUSS Saint Vincent's Hospital, Manhattan, NY. Used with permission.

6.9 Models for evaluating the effectiveness of upper-room UVGI and ventilation designs

In the USA, TUSS researchers are now undertaking development of a derived physical model, the Index of UVGI Effectiveness (Rudnick et al., 2002), which applies information such as that shown in Figure 7. This Index defines the precise relationship between UVGI exposure and particle survival, combines the number, location, and power of UVGI fixtures with room air currents, and calculates the fractional killing potential for airborne organisms. This modelling work, a part of the larger TUSS epidemiological study, will be validated by experiments in a room size chamber plus field measurements. The quantified impact of RH is being integrated into the Index of UVGI Effectiveness model.

6.10 Passive upper-room UVGI fixtures

Ultraviolet germicidal irradiation is used in several ways to prevent transmission of airborne communicable diseases. The most widely used application for UVGI is in the form of passive upper-room fixtures containing UVGI lamps that irradiate a horizontal layer of airspace above the occupants and below the ceiling. UVGI is designed to kill or inactivate microbes that enter the upper irradiated zone. UVGI systems are highly dependant on vertical room air currents to bring susceptible organisms into the irradiated zone. Even in rooms lacking mechanical ventilation, there will often be sufficient natural convective mixing to make upper-room UVGI an effective barrier to disease transmission. In fact, the lack of modern mechanical ventilation systems was one of the principal attractions for the very early uses of passive upper-room UVGI on hospital wards for patients with contagious diseases.

Modern ultraviolet fixtures (Figure 12) have been developed to control the beam of UV energy in use in the upper-room of occupied areas (Nardell et al., 1992). Special louver designs and parabolic reflectors direct a collimated beam of UV energy across the upper plane of the room. These fixtures work best for areas where floor to ceiling heights are 2,5 m to 2,8 m (8 ft to 9 ft) or greater. Where ceiling heights are greater than 2,8 m (9 ft) suspended pendant fixtures or indirect (partially opened to the ceiling) units can be used. Further research is needed to develop UVGI room delivery systems which optimize the UV output of the UV lamps in occupied areas (Dumyahn et al., 1999; Rudnick et al., 2002).

Fig. 12. Pendant and wall-mounted UVGI Fixture (instant start lamps). Source: Atlantic Ultraviolet Corp. Used with permission.

Reasons for preferring upper-room UVGI (Figures 13 to 16) applications over other air cleansing modes include the fact that:

- They are passive devices (requiring no moving parts), easily installed on existing walls and ceilings, readily accessible for inspection and maintenance, silent and inconspicuous, modest in first cost, and energy efficient (comparable to fluorescent lighting fixtures). They are applicable to all areas where people assemble.
- They have advantages over other application modes related to effectiveness in preventing airborne infectious disease transmission within rooms. Most important, infectious microbes are killed promptly because they are irradiated in the upper region of the room, very close to the locations where they are emitted into the air by an infected person. Upper-room UVGI eliminates dependence on airborne microbes becoming air-entrained into a fan-cabinet enclosure or a return air duct containing UVGI lamps, processes dependent on the real air mixing rate (in contrast to the theoretical air change rate). Upper-room UVGI has the unique characteristics of killing disease-causing microbes almost as rapidly as they are released into the air and conveyed ceiling-ward, and providing clearance rates of airborne infectious microorganisms well beyond the ability of ventilation rates alone that are still tolerable to occupants.

Fig. 13. Linear, instant start, germicidal lamps in UVGI pendant and wall mount fixtures. Source: TUSS Saint Vincent's Hospital, Manhattan, NY. Used with permission.

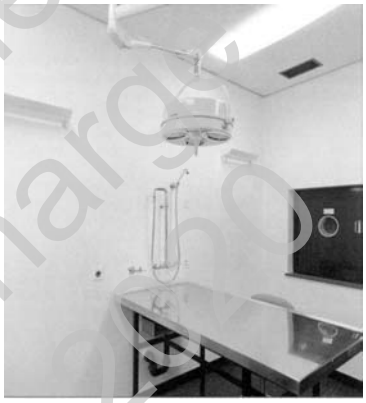

Fig. 14. UVGI fixtures directing energy upward and downward in a laboratory application to reduce infectious organisms. *WARNING: Workers in this setting must wear protective gowns and goggles to protect all exposed eye and skin surfaces from over exposure to UV-C.* Source: Philips Lighting. Used with permission.

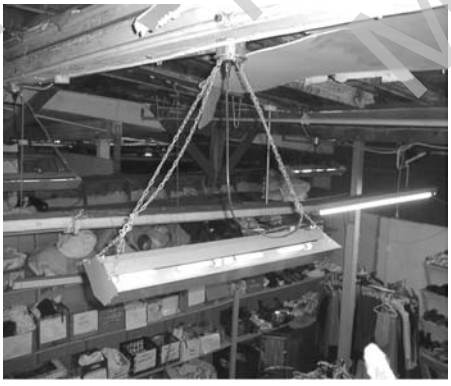

Fig. 15. Suspended UVGI fixture for high bay (> 3 m floor to ceiling height) application. Uses compact germicidal lamps. Source: TUSS Saint Vincent's Hospital, Manhattan, NY. Used with permission.

Fig. 16. Dormitory (congregate setting) using pendant mounted (compact) germicidal fixtures delivering UVGI in 360º. Source: TUSS Saint Vincent's Hospital, Manhattan, NY. Used with permission.

Although increasing room air mixing enhances upper-room UVGI effectiveness, it is clear that the resultant upflow rate is the most important characteristic because this is the flow that promptly brings airborne microbes into the killing zone. Methods for evaluating or predicting the UVGI exposure time are currently under study using advanced ultrasonic anemometers to determine vertical air speeds created by the ventilation system. It can be understood that a very rapid passage of lower-room air through the upper-room irradiated zone may provide insufficient irradiation time to kill a significant fraction of the entrained infectious organisms, but rapid vertical air circulation also implies a rapid return of the same air to the upper irradiated zone of the room for additional exposure. Ideally, one wants rapid upward air movement, plus enough UV irradiance to kill all infectious microbes during their first pass through the irradiated zone so they do not reenter the occupants' breathing zone as viable (and infective) microorganisms. This is unattainable in occupied spaces in practice, because UV irradiance is limited due to eye exposure limitations, and air mixing is limited due to comfort considerations. Therefore, only a fraction of airborne microorganisms entering the upper irradiated zone will be inactivated during a single pass. However, even when the destruction of infectious microorganisms is incomplete during a single pass through the upper irradiated zone, the down-flow of treated air provides dilution of the contagion in the lower, occupied zone as it mixes. Theoretical modelling indicates that the greatest reduction in infectious microorganisms in the breathing zone will take place when the greatest rate of air change between upper and lower-room occurs. For rooms that lack adequate air movement, the use of mixing fans is a satisfactory solution (Riley, Permutt and Kaufman, 1971).

6.11 Portable self-contained fixture UVR-fan cabinets units

Another application is the use of individual fan-cabinet units that recirculate room air over internal UVGI lamps. The protective effect of fan-cabinet room units is limited by the number of complete room air changes they can produce because their fan capacity must be restricted to avoid excessive noise, vibrations, and drafts. (see Figure 17)

Fig. 17. Enclosed room air sanitizers that irradiate entrained air with UV-C energy before discharge into the room. Pictured are a wall unit (above) and mobile stand-alone unit (right). These units are often placed in areas where upper room UVGI cannot be used because of limited floor to ceiling heights. Source: Atlantic Ultraviolet Corp. (above), NQ Environmental (right). Used with permission.

6.12 Air duct irradiation with UVR

As an energy saving feature in buildings equipped with heating, ventilating and air-conditioning systems, a large fraction of the air is recirculated before being exhausted to the outside. It has been well documented that air duct systems can carry infectious droplet nuclei through buildings (ASHRAE, 2001; Nardell, 2000; Nardell, 1998). In a measles epidemic within an elementary school equipped with central air, it was shown that the index case (the earliest documented case) contributed to the infection of twenty-eight students in fourteen different classrooms. The index case never shared the same space with those who

developed secondary infections, showing that the measles virus traveled by the ventilation system (Riley et al., 1978).

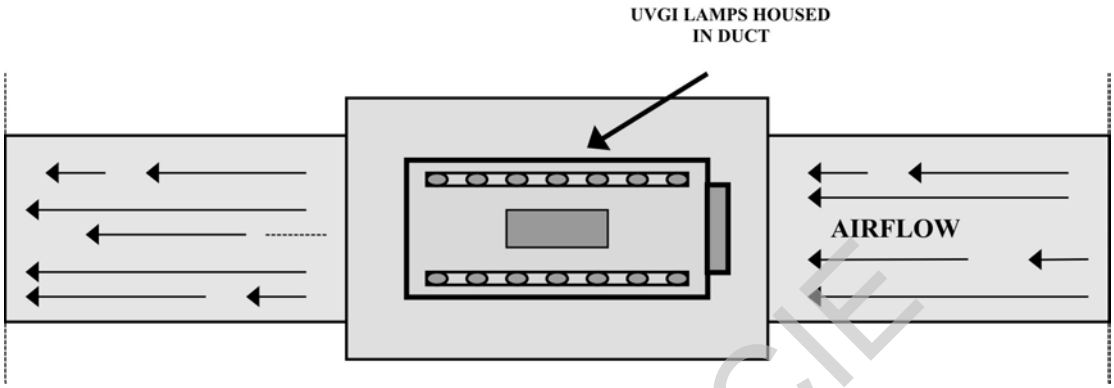

Fig. 18. Placement of linear UVGI instant start lamps in air ductwork (section view) with UVGI lamps placed perpendicular to the airflow. Source: South African Medical Research Center. Used with permission.

Fig. 19. UVGI air duct irradiation using compact preheat germicidal lamps. Left: inserting unit; middle: view of interior irradiation of duct, and right: view of portal for inspection of germicidal lamps. Source: Lumalier. Used with permission.

Lamps with sufficient UV power output may be installed in return-air ducts (Figures 18 - 19) to disinfect air leaving occupied spaces, especially when the occupants may have unsuspected diseases transmissible by the air route (for example, hospital out-patient waiting rooms). This application mode may be important when it is necessary to recirculate air (Figure 20) from these areas instead of discharging it directly to the atmosphere. However, in-duct air disinfection does little to protect occupants who are in the same room with an infectious source.

While guides for providing UVGI air-duct disinfection have existed from the 1940s, it is only in recent times that there has been renewed interest in applying modern investigation of achievable rates of air cleansing (Luckiesh, 1946; Kowalski et al., 2000a; Kowalski et al., 2000b). Current studies seek to update air-stream disinfection of air-duct systems by defining the UVGI intensity field, lamp type and placement, factors to account for intensity based on variations in surface reflectivity. There are no methods to account accurately for the impact of relative humidity, although other aerosol exposure studies could provide guidance (Ko et al., 2000; Kethley, 1978; Riley et al., 1976). Just as with other air disinfection technologies, time of exposure is critical in air duct irradiation. One advantage of the closed systems is that higher levels of UVGI can be used. Computational fluid dynamic programs are being used to explore the various interactions (Kowalski et al., 2000b). Ongoing research is needed on combinations of upper-room and in-duct strategies.

Fig. 20. In duct air irradiation (Lumalier™ ExStream system) designed for installation at the Willard Hotel Complex, Washington, DC. Disinfecting over 30 000 m^3/min and 8 m (25-foot) cooling coil. Source: Lumalier Inc. Used with permission.

6.13 UVR decontamination of surfaces

It is much more difficult to cleanse *surfaces* with UV-C, compared to UV *air* cleansing, because of UV-C's low level of penetration. Microorganisms on surfaces can be protected from UVGI based on the microorganism's decay rate constant, *K*, moisture, clumping with other particles or by shadows provided by the type of surface material (Dietz et al., 1980). Greater levels of irradiance may be necessary to achieve a given kill rate and may require special protective covering if the room is occupied, as when used in a laboratory or clinical setting (Hart, 1960a; Hart, 1960b; Phillips et al., 1955).

7. GERMICIDAL LAMPS AND BALLAST

7.1 Characteristics of germicidal lamps and ballast combinations

Action spectra research shows that the 265 nm wavelength is optimum for absorption and disruption of microbial DNA. However for practical limits of generation of UV-C, 253,7 nm commonly is chosen. Low pressure mercury-vapor germicidal lamps produce about 85% of their radiant output in 253,7 nm (see Figure 21). High intensity discharge mercury lamps produce about 15-20% of their radiant output in the germicidally effective region below 300 nm. These germicidal lamps are the source of choice for sterilization of air, surfaces and water.

Based on the same operating characteristics as general fluorescent lamps, low pressure germicidal lamps are made with fused quartz or a glass that is transparent to short-wavelength UV-C 253,7 nm radiation. These lamps are manufactured in ozone free or low ozone forms, which are used for air and surface disinfection applications. Low pressure mercury discharge lamps are produced in various lengths, shapes and diameters and with different auxiliaries required to ignite the lamp and sustain its output. The commonly used germicidal lamps are tubular T-8 (26 mm) and T-5 (16 mm) (8/8 or 5/8 inch diameter, respectively) with either preheat or rapid start ballast, starter and single or double pin connections with normal or high output features. Compact germicidal lamps are available in twin-tube and long twin-tube sizes with integrated starters. The compact germicidal lamps operate with a starter ballast combination. A recent survey shows some commercially available lamps (Table 5).

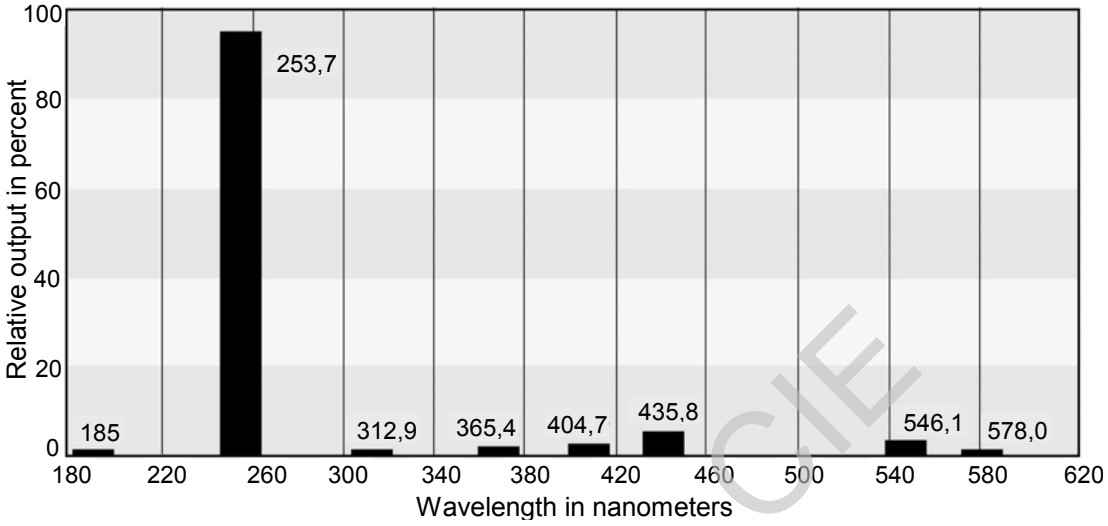

Fig. 21. Spectral power distribution curves for germicidal low-pressure mercury vapor arc lamps. Source: IESNA Lighting Handbook 9th Ed. (IESNA, 2000b) Used with permission.

7.2 Types of mercury vapor discharge lamps

There are two types of germicidal mercury vapor discharge lamps, low pressure lamps and high intensity discharge (HID) lamps. Mercury lamps were first developed in 1901. HID mercury lamps did not appear until 30 years later. Fluorescent lamps, which are low-pressure mercury arc lamps, appeared as commercial products in 1937-38 (The New Building Institute, 2001). In the 21st century, air, surface, and water disinfection is largely accomplished by low pressure mercury arc lamps and HID mercury vapor lamps. Technically, the low pressure mercury discharge lamp is one in which the partial pressure of the mercury does not exceed 100 pascals during operation while the HID mercury discharge lamp is one in which the mercury arc has a bulb wall loading in excess of 3 watts per square centimetre. The low pressure mercury lamp typically operates at a mercury pressure on the order of 1 pascal while the HID mercury lamp typically operates on the order of 10^5 pascals. The HID mercury lamp meets the definition of a *high* pressure mercury lamp (CIE, 1987) but at times is referred to as a *medium* pressure mercury lamp because there are other mercury lamps that operate on the order of 10^7 pascals. As a practical distinction for applications, there are certain parameters that differ significantly for the two lamp types, as shown in Table 4. Although the HID mercury discharge lamp has the disadvantages of higher bulb wall temperature and lower conversion efficacy than the low pressure mercury lamp, the HID type systems can be configured to achieve higher absolute irradiance levels due to higher arc radiance.

Table 4. Typical order of magnitude difference for germicidal mercury discharge lamps.

	Low Pressure	HID	
Power per unit length	0,6	50	W/cm
Bulb temperature	30	800	° C
Conversion efficacy †	0,3	0,06	W (germicidal)/W (in)
† The broadband HID radiation is evaluated based on the spectral power distribution of Figure 30.			

7.3 Low pressure mercury vapor lamps

Fluorescent lamps are low pressure mercury discharge lamps that have many properties in common with germicidal low pressure mercury discharge lamps. Because fluorescent systems are the focus of the best technology in the lighting industry, the major drivers for higher efficiency may benefit the germicidal lamp as well. Some of these drivers include: high-frequency electronic ballasts, smaller-diameter lamps, and electrodeless lamps. Because of

the rapid pace of technological innovation, lamp manufacturers should be contacted to determine which innovations might apply to germicidal applications.

Characteristics

All low pressure mercury lamps consist of a glass or quartz envelope, electrodes, and mercury. Lamp operation requires auxiliary components (ballasts and, in some cases, starters) to provide the necessary starting voltage across the lamp and to maintain the proper lamp current. When the voltage difference between the electrodes is sufficient, an electric current passes through mercury vapor within the bulb. As the current passes through the vapor, the mercury ions' electrons change energy levels; this generates visible light and ultraviolet radiation.

In the low pressure mercury fluorescent lamp, a phosphor coating on the inside of the glass envelope is excited by the UV and emits visible light as a result. Fluorescent lamp bulbs are made of soda-lime glass which blocks the emission of 253,7 nm power that is not absorbed by the phosphor. Lamp wall temperature, specifically the temperature of the coldest spot, controls the pressure of the mercury inside a mercury lamp, which in turn governs its output. Therefore it is essential that consideration be given to wall temperature based on the type of lamp (preheat, rapid start, cold or hot cathode) described below. The typical power loading for fluorescent lamps is on the order of one-half watt per centimetre of arc length.

The low pressure germicidal lamp is the same as the fluorescent lamp with two exceptions. First, the bulb is made either of fused quartz or of a special glass such as a soda barium fluoride glass that transmits the 253,7 nm mercury discharge line. Second, there is no phosphor coating. In low pressure germicidal lamps, about 60% of the electrical input power to the lamp is converted into radiant power. Of this radiant power, approximately 85% is radiated in a mercury resonance line of 253,7 nm, which is very close to the wavelength for peak germicidal efficacy. Low pressure germicidal mercury lamps emit four weak visible mercury lines. These are in the violet, blue, and yellow-green parts of the visible spectrum, causing the germicidal lamp to emit a weak bluish-white light. The spectral power distribution of a typical low-pressure germicidal lamp is shown in Figure 21.

Types of low pressure mercury lamps and operation

Cathode types

While operating principles for all fluorescent and germicidal lamps are the same, different cathodes exist, hot and cold (Gordon et al., 1995).

Cold-cathode lamp

Fig. 22. Cold-cathode germicidal lamp. Source: Atlantic Ultraviolet Co. Used with permission.

Cold-cathode lamps (Figure 22) are instant starting and utilize a thimble shaped cylinder of soft iron instead of a tungsten filament. This allows frequent starting without adversely affecting lamp life. This type of lamp maintains high output over its life. Voltage drop at the cathode is higher than with hot cathode lamps; this causes greater wattage loss, and therefore lower efficiency. Although cold-cathodes are of lower efficiency than hot cathode lamps, their longer life makes them a good choice for inaccessible areas where lamp replacement is difficult and where frequent switching is desired. They are easily dimmed. They are widely used in refrigerators and surface disinfection in unoccupied areas. Over time, output is reduced due to solarization of the glass. Maintained output for irradiation requires monitoring and change of lamp when energy output falls below a given level UV output.

Fig. 23. Miniature T-5 preheat germicidal lamp. Source: Philips Lighting. Used with permission.

In hot-cathode lamps, (Figure 23), the cathode consists of a coiled tungsten filament at each end of the bulb impregnated with electron-emissive materials. Hot-cathode lamps are operated at a higher output per unit length and with a higher overall efficiency than cold-cathode lamps, resulting in a lower cost for equal output. The superior efficiency and greater output make the hot cathode germicidal lamp more suitable in almost all room air disinfection applications.

Hot-cathode lamps are used for the majority of fluorescent and low-pressure germicidal systems. Current air and surface applications utilize four types of low-pressure mercury lamps, which are distinguished by starting and operating characteristics and designation (tubular or compact).

Preheat (tubular)

Fig. 24. Linear germicidal UV-C lamp (rapid start or preheat). Source: OSRAM Sylvania. Used with permission.

Preheat-start germicidal lamps (Figures 24-25) followed the historic development of fluorescent lamp types. In preheat lamps, cathodes must be heated electrically to emit electrons and ionize gas in the tube. This process makes preheat lamps more conductive and lowers the voltage necessary to strike the arc. Because the current heats the cathodes before the arc is struck, they are said to be preheated.

Fig. 25. Preheat 2 and 4-pin germicidal lamps. Source: Atlantic Ultraviolet Corp. Used with permission.

An automatic starter controls the preheating process, which takes a few seconds. The starter controls the time required for current to preheat the lamp's cathodes, and then shuts off. When the starter switches off, the voltage is directly applied between the cathodes, striking the arc. Once the lamp is in operation, the arc maintains the cathode temperature.

Instant start (lineal or bent)

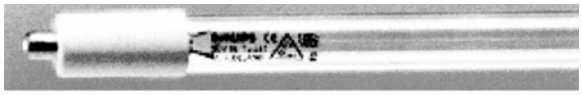

Fig. 26. Instant start single pin germicidal lamp. Source: Philips Lighting. Used with permission.

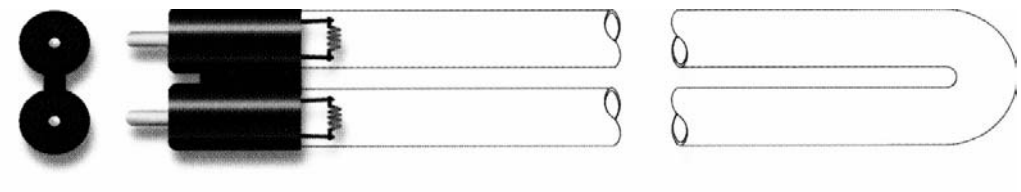

Fig. 27. Single-pin instant start germicidal lamp. Source: Atlantic Ultraviolet Corp. Used with permission.

Instant Start lamps (Figures 26-27), also known as cold start lamps and sometimes referred to as slimline germicidal lamps, are capable of operating at several current densities within their design range, 120 mA to 240 mA, depending upon the ballasts on which they are operated. This results in a range of nominal wattage values for a lamp. Because instant lamps are designed to operate without a starter, this simplifies the lighting system and its maintenance. The ballast provides sufficient voltage to strike the arc instantly, and this requires cathodes that will start without enhanced electron emission. Because preheating is unnecessary, a single-pin base is located on each end of the lamp. Some instant start lamps have bi-pin bases; however, in these lamps the pins are connected together inside the base.

Instant start lamps can be operated at more than one current and wattage. For this reason they are identified by length rather than lamp wattage, and they are normally operated at current levels of 300 mA to 420 mA. At higher current loads, the lamp wall temperature will rise above the normal value for the optimum radiation output, thereby necessitating cooling of the bulb wall. These lamps are well suited for mounting in an air-conditioning duct because of good maintenance, high initial UV output, and strong base-to-socket properties.

Rapid start (tubular)

Standard rapid-start germicidal lamps combine the features of preheat and instant-start circuits. Starters are unnecessary. The ballasts have separate windings that heat the cathodes continuously; the lamps start almost instantly after being switched on, but less voltage is required for starting than hold true for instant start lamps of comparable length. Rapid-start ballasts are less expensive, smaller, and have lower power loss than instant-start ballasts. Because the cathodes of rapid start lamps are heated continuously during operation, they can be dimmed or flashed.

High-Output (HO) rapid-start germicidal lamps operate at 800 mA compared with 300 mA to 425 mA for most standard rapid-start lamps. They produce about 45 % more output than slimline lamps of corresponding physical size because they draw considerably more current than the standard lamps. High output lamps are identified by lamp length, bulb diameter, and the inscribed letters HO.

The output of germicidal lamps decreases during operating life. There are a variety of causes, such as changes in the cathodes, blackening of the bulb walls due to deposition of evaporated cathode materials, and devitrification of the bulb wall under UV irradiation. Devitrification is a change of the bulb wall from the vitreous state to a crystalline state.

Compact germicidal lamps

Development of the fluorescent lamp family resulted in the introduction in the 1970s of compact fluorescent sources (CFLs). Germicidal lamps have been produced based on this technology.

Compact Germicidal Lamps are single-ended and produced in preheat and rapid start circuit modes. Many have starters integrated with the lamp base. As with all germicidal lamps, compact lamps require a ballast in order to start and operate properly.

(1) Standard Single-tube (2-pin) germicidal preheat lamps (Figure 28) have starter devices in the 2-pin plug base of the lamp. These lamps operate on inexpensive reactor ballasts and are available from 5 to 13 W.

Fig. 28. Single-tube, 2-pin compact germicidal lamp. Source: Philips Lighting. Used with permission.

(2) Longer Length Single-tube (4-pin) germicidal lamps (Figure 29) are designed as a higher output variation of the standard single-tube (2-pin) compact germicidal lamp; they provide a substantial increase in UV output compared to standard single-tube compact germicidal lamps. These longer length compact sources are available in rapid-start/preheat lamp versions with a 4-pin in-line base with no integrated starter. They are commonly used with external rapid-start and electronic ballasts and are dimmable.

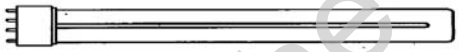

Fig. 29. Single-tube 4-pin long compact germicidal lamp. Source: Philips Lighting. Used with permission.

Output

The majority of germicidal lamps operate most efficiently in still air at 25° C temperature. Under this condition the cold spot temperature of the bulb is at or near the optimum value, at 42° C, such that most lamp types produce maximum UV emission. Ultraviolet radiation output should be measured at an ambient temperature of 25° C (IESNA, 1999; IESNA, 2000a). As with conventional fluorescent lamps, temperatures above or below this optimum value will decrease the ultraviolet radiation output, significantly so when the temperature difference is large. When lamps are operated in the confined space of a germicidal irradiation unit, the temperature of the lamp (coldest spot) is likely to be higher than optimum, with a consequential reduction of UV lamp emission below that of the lamp rating (defined at maximum lamp emission). When possible it is advantageous to control the lamp environment in an irradiation unit, such as by airflow, to maximize lamp emission. The selection of the proper germicidal lamp type should include the impact of temperature on UV-C output.

Table 5. Germicidal lamp survey for air & surface disinfection.

	Preheat Tubular Miniature	Preheat Tubular Standard	Preheat Compact	Preheat Large Compact	Instant Start (Slimline)	Cold Cathode
Nominal Lamp Wattage (W)	4-11	15-115	5-11	18-55	10-75	12-34
UV-C Output Watts (W) after 100 h burn-in	0,5-2,5	4,5-40	1,5-3,5	5,5-17	3,0-25	1,4-11,2
Approximate Length Range (mm)	150-225	450-1215	165-235	225-570	300-1700	300-1200
Nominal Diameter (mm) *	16	28-38	28 max	38 max	16-19	16
Lamp Life (h)	6 000	5 000 – 10 000	8 000	8 000	10 000	20 000
Base/Cap	Min Bipin	Med Bipin	2 pin cap	4 pin cap	Single pin	Single pin
Starter	Yes		Integrated	No	No	No
** (1) In the lighting industry, nominal tube diameter often is given as T-x where x is in eighths of an inch. The nominal diameters are 16 mm ~ T-5, 19 mm ~ T-6, 26 mm ~ T-8, and 38 mm ~ T-12. (2) The width across the two tube legs is given for compact tubes.*						

Germicidal lamps are usually identified by nominal lamp wattage, shape, length, and bulb diameter. The lamp wattage designation does not indicate the UV-C output. The manufacturer's datasheet should be consulted for rated UV-C output. A preliminary survey of commercially available low-pressure germicidal lamps shows a range of available types (hot and cold cathode) and wattages. (See Table 5) All of these are operated on either magnetic or electronic ballasts.

7.4 Medium-pressure mercury

HID mercury lamps are used when higher UV power densities are required in such applications as photocuring and water disinfection. High power load and high wall temperature characterize high output HID mercury vapor lamps. These lamps are less sensitive to variation of environmental temperature. Often, lamp ends must be cooled by forced convection to achieve a long lifetime. These lamps are made of fused quartz, and the spectral output is spread over a broader range of wavelengths because of the high mercury pressure (see Figure 30). The average UV-C output is 10-15% of the radiant flux of the lamp depending on the absorption of ozone. The efficiency for germicidal action amounts to 80% of the total UV-C output.

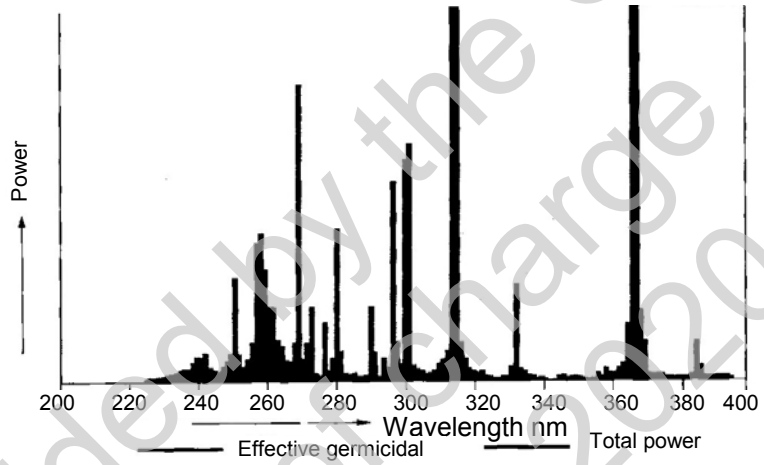

Fig. 30. Typical spectral power distribution of medium-pressure mercury vapor source.

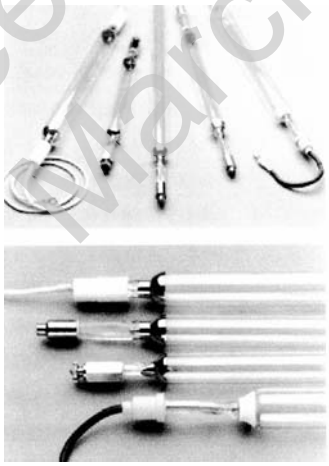

Fig. 31. Series of medium-pressure germicidal lamps. Source: Jelight Co. Used with permission.

7.5 Ozone

The low pressure mercury arc discharge lamps, as well as many HID mercury lamps, generate a weak line at 185 nm as well as the strong line at 253,7 nm in the UV-C. 185 nm radiation will convert atmospheric oxygen to ozone, a powerful oxidizing agent that is both

toxic to humans and highly corrosive. Because of its toxicity, limitations on ozone levels have been established to address environmental and safety concerns (ACGIH, 2003). While there are some germicidal irradiation applications that may be enhanced by ozone, for example water purification processes, ozone is considered a biohazard in air disinfection applications; careful consideration of appropriate application is required so that occupational safety is maintained. Germicidal lamps are available in two general categories. Ozone-producing lamps have bulbs, commonly certain types of fused quartz that transmits 185 nm. Ozone-free lamps have bulbs made of glass or of a fused quartz doped to block radiation below 200 nm. Only ozone-free germicidal lamps should be considered for air disinfection.

7.6 Maintenance

Because most air and surface disinfection will be in critical high risk settings for airborne disease control, they will be operated 24h/7days/week. In order to maintain optimum output for UV disinfection, a system for monitoring output must be in place. In health care settings this may be part of the infection control plan with in-service training required and designated personnel assigned to monitor output at regular intervals. Other settings will require training of maintenance personnel (or enlisting a qualified lighting maintenance company). A radiometer designed to read UV-C output will be required. Output levels for disinfection should be designated so intervention can take place either by cleaning of the lamp, lamp fitting or lamp replacement. Manufacturers' recommendations for relamping should be followed.

7.7 Energy and environment issues - Mercury

It can be argued that the environmental benefit of germicidal disinfection is two-fold for the environment in that it is a sound use of a mercury-based technology for which there is no known substitute. Further, it is a low energy-intensive technology (UV disinfection potential vs. equivalent amounts of conditioned air for dilution). The energy required to produce conditioned outside air compared to the disinfection potential of germicidal UV would generate far greater environmental mercury from the present day fuels used to generate the electricity. The lighting industry is gradually reducing the level of mercury in fluorescent systems and this trend is occurring with some germicidal lamps. However, a certain amount of mercury will be required to produce the germicidal irradiation and should be allowed. Proper environmental disposal of spent lamps is required.

7.8 Ballast

Ballast for low pressure mercury lamps

Fluorescent lighting technology is rapidly changing to generate greater efficiencies through smaller diameter [16 mm, (T-5)] lamps and electronic ballasts. There is a shift toward high-frequency electronic ballasts with advanced circuitry to track lamp changes over life and to produce better performance. Some of these aspects appear in current germicidal air disinfection applications with tunable circuitry to allow either an adjustment upward over life to maintain UV output or to dim the lamp to prevent stray irradiation. There is a general shift to electronic ballasts in commercially available UVGI fixtures.

Characteristics

Ballast types

Three types of ballasts can be used with germicidal lamps. (1) Magnetic: an inefficient device that uses a core and coil assembly transformer to perform the minimum functions required to start and operate the lamp. (2) Hybrid or "low frequency electronic": essentially a magnetic ballast with a few electronic components that switch off voltage to rapid start lamp coils once the lamp has started. A minimal increase in efficiency is obtained via more expensive magnetic core material and the absence of power to the lamp coils during operation. (3) High frequency electronic: a ballast that operates lamps at frequencies above 20 000 Hz. Maximum efficiency is obtained through the use of electronic circuitry and optimum lamp operating characteristics.

Ballasts have two primary functions: (1) start the lamp and (2) control operation of the lamp once it has started. High frequency electronic ballasts operate lamps more efficiently

(30-40% than magnetic ballasts at equivalent light output) and eliminate the hum and visible flicker normally associated with standard magnetic ballasts. Electronic ballasts also typically have better power quality than magnetic ballasts (higher power factor and lower total harmonic distortion). Rigorous testing procedures and standards specifically for UV lamp and ballast combinations are not currently available, but testing procedures for fluorescent lamps are applicable to low pressure germicidal lamps.

Instant start vs. rapid start

Instant start (high voltage is applied across the lamp with no preheating of the cathode) is the most energy efficient starting method for fluorescent lamp ballasting. Instant start ballasts use 1,5 to 2 watts less per lamp than rapid start ballasts (low voltage is applied to the cathodes prior to lamp ignition and is maintained throughout operation). Other instant start ballast benefits typically include parallel lamp circuitry, longer remote wiring distance, easier installation due to less complicated wiring, and capability to start lamps at –18° C (0° F) versus 10° C (50° F) for rapid start.

Ballast factors - Definitions of terms

Ballast Factor (BF): The relative light output of a lamp(s) on the subject ballast compared to that on a reference ballast circuit. For example, a ballast factor of 0,90 means that the lamp light output is only 90% of the rated value. The ballast factor can be used with low pressure mercury lamps by using the UV-C output instead of light output.

Ballast Efficacy Factor (BEF): The ballast factor (expressed in percent) divided by input power (watts) to the ballast. Ballast efficacy factor is used to measure the level of efficiency of similar ballast models. For example, a ballast which has a ballast factor of 90 and input watts of 59 (BEF = 1,53) is more efficient than another ballast with ballast factor of 87,5 and input watts of 62 (BEF = 1,41). This factor is also applicable to germicidal lamp systems.

Ballast Life: To maximize life, the ballast ambient temperature should be kept as low as possible. It is also important to maintain effective dissipation of heat using the germicidal fixture as a heatsink for the ballast enclosure. Some ballasts are designed to have a life expectancy of 60 000 hours.

Ballast Losses: Power consumed by ballast that dissipates as heat instead of being delivered to the lamps. Electronic ballasts operate more efficiently than magnetic or hybrid ballasts.

Ballasts for high intensity discharge (HID) mercury lamps: Ballasts for HID mercury vapor discharge lamps generally serve the same objectives as for low pressure mercury vapor lamps. The two most important issues are starting the lamp and controlling the power to the lamp. Testing procedures for HID lighting lamps can be used if proper precautions are taken for protection against UV and ozone hazards.

8. HEALTH AND SAFETY GUIDANCE FOR HUMAN EXPOSURE TO UVR

Over the past three decades, occupational health and safety officials have provided guidance for worker environmental exposure to ultraviolet radiation (NIOSH, 1972). Overexposure to UV-C can result in transient conjunctival irritation (photoconjunctivitis) and skin irritation (erythema), which disappear within a 24-48 hour period without lasting biological damage (CIE, 2002).

8.1 Monitoring daily exposure to stray UVR

Eye and skin exposure time limit the practical usage of UVGI during human occupancy of living spaces. Threshold limit values (TLV) have been recommended by the American Conference of Governmental Industrial Hygienists (ACGIH) and appear in many guidelines, standards and regulations (Sliney, 2000; ACGIH, 2003). International harmonization efforts are under way to account for concerns of the photobiological potential of electric lamps (CIE, 2002). This effort is possible because of recently issued recommended practices for quantifying light sources' safe application (Sliney, 1991; ANSI/IESNA, 2000; ANSI/IESNA 1996a; ANSI/IESNA, 1996b; IESNA, 1996; Drop, 1998; Landry et al., 1998; Levin, 1998). Balancing the need to protect room occupants while maximizing UVGI in the upper room raises questions about the application of the TLVs. There is potential overexposure to UV-C

for occupants of spaces treated with upper room UVGI through stray radiation in the lower part of the room or direct exposure of maintenance personnel working in the upper room. The latter concern is dealt with by proper staff training. Special key-switches safeguard unauthorized activation or deactivation of the systems. The ACGIH exposure limit (TLV) for 253,7 nm UV is 6 mJ/cm^2 for any 8 h period. This equates to 8 h continuous eye exposure at 0,002 W/m^2 (0,2 μW/cm^2). UVGI application engineers have used this irradiance level as the maximal UV flux permitted at eye level (172,7 cm) at any location in the room. It is assumed that an individual is continuously exposed and with an orientation to receive this 0,002 W/m^2 (0,2 μW/cm^2) on the eye's surface. This design and commissioning guide has resulted in very conservative installations. In TUSS (Brickner et al., 2000), no authenticated incidents of photoconjunctivitis or skin erythema have been described to date (1997-2002).

TUSS scientists are now using 0,004 W/m^2 (0,4 μW/cm^2) at eye level as their design criteria. This takes into account the body's designed defenses: shading of upper lids and brows, turning of the head and numerous other factors which limit human eye exposure to the maximum UVGI irradiance in the lower room to a modest fraction of the time that person spends in the room. Experiments are under way at HSPH to test various monitoring media to determine patterns of UV exposure in a dynamic mode in order to understand the cumulative 8 h dose (Rahn et al., 1999; Nardell et al., 2002). (See Figure 32)

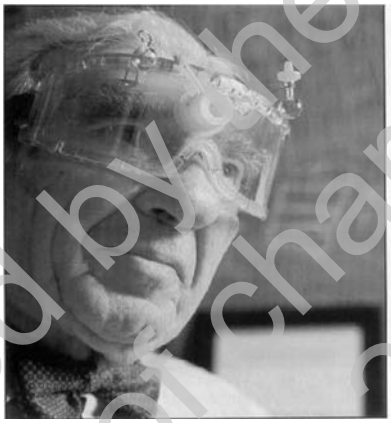

Fig. 32. Actinometers mounted on goggles to determine dynamic eye exposure to UVGI systems. Source: Kent Dayton/Harvard School of Public Health, Harvard Review 1999. Used with permission.

8.2 HIV - Human Immune Deficiency Virus mutation

Does the use of UV-C pose any risk for activating HIV or does UV exposure cause mutant HIV strains to develop? This question is posed by Valerie (Valerie et al., 1999) who pointed out that UV-C was much more potent in activating HIV in cell culture than was ionizing radiation. However, if HIV mutations were occurring in vivo, they would presumably be evidenced in persons exposed to the solar spectrum with its far greater levels of biologically potent (UV-A and UV-B) wavelengths, rather than comparatively trivial amounts of UV-C allowed in the lower room <0,002 W/m^2 (< 0,2 μW/cm^2). Saah (Saah et al., 1997) did not find any epidemiological evidence that solar ultraviolet exposure exacerbated the HIV status in a group of 1 155 white males. He developed a UV index of sensitivity (eye, hair colour and skin type), recorded UV exposure history (sunlight, tanning beds, beach time and use of sun screen), and a composite score of both UV sensitivity and exposure. He then compared these to rate of CD4 decline and progression to AIDS. No correlation was found. In fact, those seeking the sun tended to be healthier. Gelfand (Gelfand et al., 1998), in a controlled study, evaluated therapeutic UV-B exposure, the wavelength most likely to be of concern because it produces greater penetration than UV-C and greater biologic activity than UV-A. Twelve HIV-positive patients with UV-responsive skin problems were treated, and both viral load and CD4 counts were followed for 8 weeks. There were no changes, despite levels of direct UV exposure that are many times greater than those in the lower room when UV-C, which is less-penetrating than UV-B, has been installed in the upper room.

8.3 Protective measures for workers if UV sources were used in open

When working in an irradiated zone, workers should wear industrial clothing (heavy fabric), and industrial face protection (e.g., face shields). Full-face respirators also serve this purpose.

Safe and effective use

Proper installation and use is critical for both safety and efficacy. Improper installations have led to accidents with painful eye irritation (photokeratitis) and skin erythema (Murray, 1990). It is important to use properly designed fixtures to direct UV energy away from the face and eyes. Other safety factors include:

Eye and face protection - Clear plastic face shields, goggles, spectacles (no face protection);

Filter materials—Filtering materials: glass - soft, lime glass absorbs UV-C, UV-B, quartz and high silica glass transmits UV-C, clear plastics absorb most UV-C, UV-B and generally contain absorbers to limit aging.

8.4 UV impacts on plants and materials

Upper room irradiation can cause some types of plants to wilt and die. Hanging plants should be removed from these areas of disinfection. Additionally, as with other forms of UV, UV-C can cause paints and other materials to fade and degrade over time.

8.5 Carcinogenic effects

Long-term exposure to solar UV radiation is recognized as a major cause of nonmelanoma skin cancer (NMSC) in man, but exposure to any UV radiation can in theory contribute to this risk. Basal cell carcinoma (BCC) accounts for more than 70 % of all NMSC, and episodic severe sunburns in childhood may be an important risk factor (Humphreys, 2001).

Squamous cell carcinoma (SCC) represents the remaining NMSC incidence, and chronic cumulative UV exposure is important for its development (Humphreys, 2001). A tentative UV action spectrum for SCC has been developed from an animal model using reasonable assumptions (CIE, 2000). This action spectrum indicates that the carcinogenicity of UV radiation at 254 nm is approximately two orders of magnitude less than at the maximum sensitivity, i.e., in the principal solar tanning region near 300 nm. Exposure to UVGI at or below the recommended safe exposure dose is unlikely to be a measurable factor in NMSC incidence.

8.6 Warnings

It is imperative to alert facilities maintenance and operational staff to potential hazards of direct exposure to UVGI when working in the upper-room where UVGI fixtures are installed. The IEC has developed an international symbol to be provided on the UV-C lamp or its immediate wrapping or container shown in Figure 33.

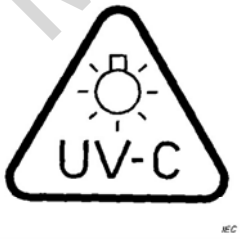

Fig. 33. Germicidal lamps international symbol © IEC: 1996, 61549-IEC-04-1.

Placement of this symbol is not required if a written cautionary notice is provided. Multilingual signage needs to be developed.

A suggested written warning could be as follows:

WARNING! Danger of UV-C exposure! Exposure to germicidal ultraviolet irradiation can cause injury to the eyes and skin. These are primarily acute effects (conjunctivitis, keratitis,

and erythema) that follow hours of exposure, the latency decreasing with increasing dose. Because there is no immediate indication during an exposure, it is important to protect eyes and skin from direct germicidal lamp exposure.

9. CONCLUSIONS AND RECOMMENDATIONS

Public safety and health concerns have brought a renewed interest in updating UVGI application information with studies of efficacy, definitive testing for required UV dose to kill infectious microorganisms, dosimetry, personal UV monitors, standardized methods of testing UVGI systems and components (lamps, fixtures and ballasts), and development of design guidelines and computer programs for application in high-risk settings. Several CIE committees are developing input which will contribute to this body of knowledge. Work is currently underway to determine real world efficacy of UV through an epidemiological study, which aims to develop a state-of-the-art UV air disinfection model.

New challenges face humanity in the 21st century as microbes continue to develop resistance to antibiotics (CDC, 2002c). The spectre of "designer" microbes also exists, which may be created for malicious use (Whitehouse, 2002). In order to develop verifiable protection of air and surfaces from contagious microbes, further scientific investigation is warranted. It is important to develop a common database of decay rate constants for a range of viruses, bacteria (vegetative and spore) and fungi based on aerosol generation, particle sizes and concentrations, organism viability, infectivity and virulence, airflow and climate (temperature and relative humidity). This will allow an assessment of engineering control strategies for prevention of airborne transmission where ventilation, filtration and UVGI can be optimized. Major engineering firms are using computational fluid dynamics (CFD) to develop ventilation designs; therefore, advanced engineering models incorporating upper-room and air-duct irradiation into CFD need to be validated as tools in order for building design and operation professionals to create and verify installations. Wider cooperation is needed between branches of microbiology, architecture and engineering (ventilation, filtration and lighting specialists) to develop cross-disciplinary application guidelines. Research and development is needed to provide new open fixtures that optimize the upper-room irradiation while limiting stray radiation into occupied areas. This may require different germicidal lamps (miniature and circular) for lamp and fixture optimization. Current fluorescent lamp testing procedures could be adapted to standardized measurement of UV-C output. Further work is needed to validate UVGI air duct irradiation. There exists much information that can be adapted for use today. The goal is to advance the science of UV technology to a new level of applicability.

GLOSSARY

For the purposes of this technical report, the following definitions, symbols and abbreviations were adapted and applied (CDC, 1994; CDC, 2001a; CIE, 1987; Serpone et al., 2002; Braslavsky et al., 1996).

Absorption [see ILV 845-04-74 (CIE, 1987)]

Process by which radiant energy is converted to a different form of energy by interaction with matter.

The absorption (of electromagnetic radiation) is the transfer of energy from an electromagnetic field to an entity (molecular or otherwise).

Acceptable indoor air quality

Air in which there are no known contaminants at harmful concentrations as determined by knowledgeable authorities and with which a substantial majority (≥ 80%) of the people exposed do not express dissatisfaction.

ACGIH - American Conference of Governmental Industrial Hygienists

Acid-fast bacilli (AFB)

Bacteria that retain certain dyes after being washed in an acid solution. Most acid-fast organisms are mycobacteria. When AFB are seen on a stained smear of sputum or other

clinical specimen, a diagnosis of TB should be suspected; however; the diagnosis of TB is not confirmed until a culture is grown and identified as M. tuberculosis.

Actinism [see ILV 845-06-02 (CIE, 1987)]

Property of optical radiations which enables them to cause chemical changes on certain living or non-living materials.

Actinometer

A chemical system or physical device which determines the number of photons in a beam integrally or per unit time. This name is commonly applied to devices used in the ultraviolet and visible wavelength ranges. For example, solutions of ferrioxalate can be used as a chemical actinometer, while bolometers, thermopiles, and photodiodes are physical devices giving a reading that can be correlated to the number of photons detected.

Actinometry

The process by which the number of photons emitted from a radiation source is determined using an actinometer.

Action spectrum

A plot of a relative biological or chemical photoresponse per number of incident photons of a monochromatic radiation, against wavelength or photon energy under the same radiant power of radiation. This form of presentation is frequently used in the studies of biological or solid state systems, where the nature of the absorbing species is unknown. The action spectrum is sometimes called spectral responsivity or sensitivity spectrum. The precise action spectrum is a plot of the spectral (photon or quantum) effectiveness. By contrast, a plot of the biological or chemical change or response per absorbed photon (quantum efficiency) versus wavelength is the efficiency spectrum.

Aerosol

Particles of respirable size generated by both humans and environmental sources and that have the capability of remaining viable and airborne for extended periods in the indoor environment.

AIA

American Institute of Architects. Professional group responsible for publishing the “Guidelines for Design and Construction of Hospitals and Healthcare Facilities”, a consensus document for design and construction of health care facilities endorsed by the U.S. Department of Health and Human Services, healthcare professionals, and professional organizations.

Air changes per hour (ACH)

The ratio of the volume of air flowing through a space in a certain period of time (i.e., the airflow rate) to the volume of that space (i.e., the room volume); this ratio is usually expressed as the number of air changes per hour (ACH). See Equivalent air change (ACH_{eq}).

Air mixing

The degree to which air supplied to a room mixes with the air already in the room, usually expressed as mixing factor. This factor varies from 1 (for perfect mixing) to 10 (for poor mixing), and it is used as a multiplier to determine the actual airflow required (i.e., the recommended ACH multiplied by the mixing factor equals the actual ACH required). For effective upper room air disinfection, mixing between the upper and lower room is essential. Mixing is also necessary for effective air disinfection by ventilation or filtration.

Air conditioning

The process of treating air to meet the requirements of a conditioned space by controlling its temperature, humidity, cleanliness, and distribution.

Airborne transmission

A means of spreading infection when airborne droplet nuclei (small particle residue of evaporated droplets ≤ 5 μm in size containing microorganisms that remain suspended in air for long periods of time) are inhaled by the susceptible host.

Air-cleaning system

A device or combination of devices applied to reduce the concentration of airborne contaminants (i.e., microorganisms, dusts, fumes, aerosols, other particulate matter, gases).

Air diffuser

The grille plate which disperses the air stream coming into the conditioned air space.

Alveoli

The small air sacs in the lungs that lie at the end of the bronchial tree; the site where carbon dioxide in the blood is replaced by oxygen from the lungs and where TB infection usually begins.

Ambient air

The air surrounding an object.

Anemometer

A meter which measures the velocity of air. An anemometer is often used as a means of determining the volume of air being drawn into an air sampler.

ASHE - American Society of Hospital Engineers, an association affiliated with the American Hospital Association.

ASHRAE - American Society of Heating, Refrigerating, and Air Conditioning Engineers Inc.

Basal cell carcinoma (BCC) (see the US National Cancer Institute's Online Cancer Dictionary)

A type of skin cancer that arises from the basal cells, small round cells found in the lower part (or base) of the epidermis, the outer layer of the skin.

Bacillus of Calmette and Guerin (BCG) vaccine

TB vaccine used in many parts of the world.

Biosafety level

A combination of microbiological practices, laboratory facilities, and safety equipment determined to be sufficient to reduce or prevent occupational exposures of laboratory personnel to the microbiological agents they work with. There are four biosafety levels based on the hazards associated with the various microbiological agents.

Bunsen-Roscoe law [see CIE 106-1993 (CIE, 1993)]

A photochemical reaction will also exhibit reciprocity between irradiance (exposure dose rate) and exposure duration. This is termed the “Bunsen-Roscoe law”. That is, a given radiant exposure in J/m^2 is required to elicit a given response regardless of exposure duration over a wide range of exposure durations. Repair mechanisms, recombination over long periods and photon saturation for extremely short periods will lead to reciprocity failure. The product of irradiance E in W/m^2 and exposure duration t is the radiant exposure H in J/m^2, i.e., $H = E \cdot t$

While both E and H may be defined over the entire optical spectrum, it is necessary only to weight these quantities over the extent of the action spectrum for photochemical effects.

CFU/m^3

Colony forming units per cubic meter (of air).

Commissioning (a room)

Testing a system or device to ensure that it meets the pre-use specifications as indicated by the manufacturer or predetermined standard.

Conditioned space

That part of a building that is heated or cooled, or both, for the comfort of the occupants.

Contaminant

An unwanted airborne constituent that may reduce acceptability of the air.

Convection

The transfer of heat or other atmospheric properties within the atmosphere or in the airspace of an enclosure by the circulation of currents from one region to another, especially by such motion directed upward.

Decay rate constant (microbe susceptibility) (*K*)

The constant, *K* is a measure of intrinsic microbe susceptibility to UVGI. Unit: m^2/J.

Direct transmission

Involves direct body surface-to-body surface contact and physical transfer of microorganisms between a susceptible host and an infected/colonized person, or exposure to cloud of infectious particles within 3 feet; particles are >5 μm in size.

Disinfection

A generally less lethal process of microbial inactivation (compared to sterilization), which eliminates virtually all recognized pathogenic microorganisms but not necessarily all microbial forms (e.g., bacterial spores). In disinfection the concentration of microorganisms (not spores) is reduced by a factor between 10^{-3} to 10^{-5}.

DNA (deoxyribonucleic acid)

One of two types of molecules that encode genetic information. (The other is RNA. In humans DNA is the genetic material; RNA is transcribed from it. In some other organisms, RNA is the genetic material and, in reverse fashion, the DNA is transcribed from it.)

DNA is a double-stranded molecule held together by weak hydrogen bonds between base pairs of nucleotides. The molecule forms a double helix in which two strands of DNA spiral about one other. The double helix looks something like an immensely long ladder twisted into a helix, or coil. The sides of the "ladder" are formed by a backbone of sugar and phosphate molecules, and the "rungs" consist of nucleotide bases joined weakly in the middle by the hydrogen bonds.

There are four nucleotides in DNA. Each nucleotide contains a base: adenine (A), guanine (G), cytosine (C), or thymine (T). Base pairs form naturally only between A and T and between G and C so the base sequence of each single strand of DNA can be simply deduced from that of its partner strand.

The genetic code in DNA is in triplets such as ATG. The base sequence of that triplet in the partner strand is therefore TAC.

The first proof that DNA was the hereditary material was provided in 1944 by Oswald Avery, Maclyn McCarty and Colin MacLoed. The double helical structure of DNA was discovered in 1953 by James D. Watson and Francis H.C. Crick with the invaluable collaboration of the X-ray crystallographer Rosalind Franklin. Watson and Crick shared the 1962 Nobel Prize in Physiology or Medicine with Maurice H.F. Wilkins. (Source: www.medterms.com 4/23/02).

Dose (of optical radiation of specified spectral distribution) [see ILV 845-06-21 (CIE, 1987)]

Term used in photochemistry, phototherapy and photobiology for the quantity radiant exposure.

unit: $J \cdot m^{-2}$

Further explanation: In other words, the energy (in Joules) or amount of photons (in mols) absorbed per unit area or unit volume by an object irradiated during a given exposure time. In medicine and in some other research areas, the term dose is used in the sense of fluence, that is the energy or amount of photons per unit area or unit volume **received** by an irradiated object during a particular exposure time. See also Germicidal dose.

Droplets

Particles of moisture, such as are generated when a person coughs or sneezes, or when water is converted to a fine mist by a device such as an aerator or shower head. Intermediate in size between drops and droplet nuclei, these particles, although they may still contain infectious microorganisms, tend to quickly settle out from the air so that any risk of disease transmission is generally limited to persons in close proximity to the droplet source.

Droplet nuclei

Evaporation of droplets of various size expelled into the air when an infectious person coughs or sneezes, or spread maliciously, form aerodynamic droplet nuclei (1 μm - 5 μm in diameter) which may contain infectious particles which can remain airborne for extended periods of time. These droplet nuclei if inhaled into the extremities of the lungs (air sacks) can cause respiratory infection. For example, the droplets produced by an infectious TB patient when coughing, sneezing, or talking can carry tubercle bacilli and can remain suspended in the air for prolonged periods of time and be carried on normal air currents in the room.

Drug resistance, acquired

A resistance to one or more anti-TB drugs that develops while a patient is receiving therapy and which usually results from the patient's non adherence to therapy or the prescription of an inadequate regimen by a health-care provider.

Drug resistance, primary

A resistance to one or more anti-TB drugs that exists before a patient is treated with the drug(s). Primary resistance occurs in persons exposed to and infected with a drug-resistant strain of M. tuberculosis.

Effective exposure dose

Time integral of effective irradiance.

Equivalent Air Change (ACH_{eq})

The number of theoretical room air changes in a well-mixed room that would be required to reduce the number of viable airborne bacteria to the same degree as the UV irradiation alone.

Erythema (actinic) [see ILV 845-06-15 (CIE, 1987)]

Reddening of the skin, with our without inflammation, caused by the actinic effect of solar radiation or artificial optical radiation.

Note: Non-actinic erythema can be caused by various chemical or physical agents.

Exhaust air

Air removed from a space and not reused therein.

Exposure

The condition of being subjected to something (e.g., infectious agents, irradiation, particulates, or chemicals) that could have harmful effects. For example, a person exposed to M. tuberculosis does not necessarily become infected (see Transmission).

Exposure dose

Radiant exposure (J/m^2 unweighted) incident on biologically relevant surface.

Fixed room-air HEPA recirculation systems

Nonmobile devices or systems that remove airborne contaminants by recirculating air through a HEPA filter. These may be built into the room and permanently ducted or may be mounted to the wall or ceiling within the room. In either situation, they are fixed in place and are not easily movable.

Fluence (at a point for a given duration) **($H_{e,o}$)** [see ILV 845-01-45 (CIE, 1987)]

Time integral of the spherical irradiance (fluence rate) Ee,o at the given point over a given duration.

Further explanation: When applied to energy, it is the total radiant energy traversing a small transparent imaginary spherical target containing the point under consideration, divided by the cross section of this target. The product of the fluence rate and the duration of the irradiation ($\int E_{e,o} dt$, simplified expression: $H_{e,o} = E_{e,o} \cdot t$ when the fluence rate is constant over the time considered). The SI unit is J/m^2. Energy fluence is identical to spherical radiant exposure and reduces to radiant exposure (H) for a parallel and normally incident beam, not scattered or reflected by the target or its surroundings. See also dose.

Fluence rate (at a point) **(E_o)** [see ILV 845-01-40 (CIE, 1987)]

Quotient of the radiant flux of all the 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.

Further explanation: When the radiant power is constant over the solid angle considered the rate of fluence, $H_{e,o}$ is four times the ratio of the radiant power, Φ_e, incident on a small transparent imaginary spherical volume element containing the point under consideration, divided by the surface area of that sphere, A_K. ($\int_{4\pi} L \, d\omega / A_K$, simplified expression: $E_{e,o} = 4 \, \Phi_e / A_K$.) For energy fluence rate the SI unit is W/m^2. It reduces to irradiance, E, for a parallel and perpendicularly incident beam not scattered or reflected by the target or its surroundings. See radiant intensity, radiance and spherical irradiance.

Flux (energy flux)

See radiant energy flux, radiant power.

Fomites

An inanimate object (linens, books, dishes, or other objects used or touched by a patient) that may be contaminated with microorganisms and serve in their transmission.

Germicidal effectiveness

The capacity of various portions of the ultraviolet (UV) spectrum to destroy bacteria, fungi, and viruses.

Germicidal efficiency of radiant flux

The ratio of the germicidal effectiveness of that wavelength to that of wavelength 265,0 nm, which is rated as unity.

Germicidal exposure (dose)

The product of germicidal flux density on a surface and time. It usually is measured in germicidal μW · min/cm^2 or germicidal W · min/ft^2.

Germicidal fluence

The fluence $H_{e,o}$ weighted with the germicidal action spectrum $s_g(\lambda)$ according to equation (1).

The germicidal weighted fluence $H_{o,g}$ is defined by:

$$H_{o,g} = \int_{200}^{400} s_g(\lambda) \cdot H_{o,\lambda}(\lambda) \cdot d\lambda \quad (1)$$

where $s_g(\lambda)$ is the relative spectral sensitivity of the microorganism. If the normalisation of the function $s_g(\lambda)$ is performed in such a way that $s_g(254) = 1$ the value of $H_{o,g}$ gives the same inactivation as a fluence H_o of radiation at 254 nm with the same value.

$H_{o,\lambda}(\lambda)$ is the spectral fluence (the spectrum of the radiation) in J/m^{2}nm.

For practical reasons the integration may be replaced by summation:

$$H_{o,g} = \sum_{200}^{400} s_g(\lambda) \cdot H_{o,\lambda}(\lambda) \cdot \Delta\lambda \quad (2)$$

exposure rate should not be used for microorganisms, instead fluence rate must be used (W/m^2).

Unit: J/m^2.

Germicidal fluence rate

The fluence rate $E_{e,o}$ weighted with the germicidal action spectrum $s_g(\lambda)$.

Unit: W/m^2.

Germicidal flux

Radiant flux evaluated according to its capacity to produce germicidal effects. It usually is measured in microwatts of UV radiation weighted in accordance with its germicidal efficiency. Such quantities of germicidal flux would be in germicidal microwatts.

Note: Ultraviolet radiation of wavelength 253,7 nm usually is referred to as “ultraviolet microwatts” or “UV watts.”

Germicidal flux irradiance

The germicidal flux per unit area of the surface being irradiated. It is equal to the quotient of the incident germicidal flux divided by the area of the surface when the flux is uniformly distributed. It usually is measured in μW/cm^2 or W/ft^2 of germicidally weighted UV radiation (germicidal μW/cm^2 or germicidal W/ft^2).

Germicidal lamps

Mercury vapor arc lamps that emit a significant portion of its radiative power in the UV-C band (100 nm to 280 nm). Germicidal lamps emit ultraviolet germicidal irradiation (UVGI), (predominately at the 253,7 nm wavelength, within the UV-C bandwidth), to kill or inactivate microorganisms. Germicidal lamps can be used in ceiling or wall fixtures or within air ducts of ventilation systems.

Germicidal radiation [see ILV 845- 06-20 (CIE, 1987)]

Optical radiation capable of killing pathogenic microorganisms.

HEPA filtration

High Efficiency Particulate Air (HEPA) filtration.

HEPA filter

High Efficiency Particulate Air filters capable of removing 99,97% of particles 0,3 μm in diameter (and having higher efficiencies for larger particles) may assist in controlling the

transmission of airborne disease agents. These filters may be used in ventilation systems to remove particles from the air or in personal respirators to filter air before it is inhaled by the person wearing the respirator. The use of the HEPA filter in ventilation systems requires expertise in installation and maintenance. To test this type of filter, 0,3 μm particles or dioctylphthalate (DOP) are drawn through the filter. Efficiency is calculated by comparing the downstream and upstream particle counts. The optimal HEPA filter allows a maximum of three 0,3 μm diameter particles to pass through for every 10 000, 0,3 μm diameter particles that are fed into the filter.

HEPA recirculation units

Free-standing portable devices that remove airborne contaminants by recirculating air through a HEPA filter.

Human immunodeficiency virus (HIV) infection

Infection with the virus that causes acquired immunodeficiency syndrome (AIDS). HIV infection is the most important risk factor for the progression of latent TB infection to active TB.

HVAC

Heating, Ventilation, Air Conditioning.

Immunosuppressed

Persons are at greatly increased risk for developing active TB after they have been infected with M. tuberculosis. No data are available regarding whether these persons are also at increased risk for infection with M. tuberculosis after they have been exposed to the organism.

Infection

The condition in which microorganisms enter the body and either cause disease or increase the probability of disease in the future.

Infectious

Capable of transmitting infection. For example, when persons who have clinically active pulmonary or laryngeal TB disease cough or sneeze, they can expel droplets (which can evaporate and become droplet nuclei containing M. tuberculosis) into the air.

Infectious particles

Sufficiently small particles (1 μm – 5 μm in diameter) introduced into the environment through natural or malicious sources that can remain airborne indefinitely and cause infection when a susceptible person is exposed at or beyond 1 m (3 feet) of particle source.

Installation flux density (for an interior lighting) [see ILV 845- 09-48 (CIE, 1987)]

Quotient of the sum of the individual total fluxes of the luminaires of an installation, by the floor area.

unit: $\mathrm{lm \cdot m^{-2}}$

Irradiance (at a point of a surface) **(E_e; E)** [see ILV 845-01-37 (CIE, 1987)}

Quotient of the radiant flux $\mathrm{d}\Phi_e$ incident on an element of the surface containing the point, by the area $\mathrm{d}A$ of that element.

Equivalent definition. Integral, taken over the hemisphere visible from the given point, of the expression $L_e \cdot \cos\theta \cdot \mathrm{d}\Omega$, where L_e is the radiance at the given point in the various directions of the incident elementary beams of solid angle $\mathrm{d}\Omega$, and θ is the angle between any of these beams and the normal to the surface at the given point.

$$E_e = \frac{d\Phi_e}{dA} = \int_{2\pi sr} L_e \cdot \cos\theta \cdot d\Omega \qquad \text{unit: W} \cdot \text{m}^{-2}$$

Further explanation: When the radiant flux or radiant power, Φ_e is incident on an infinitesimal element of surface containing the point under consideration and is constant over the surface area then divided by the area of the element results in the irradiance ($d\Phi_e/dA$, simplified expression: $E = \Phi_e/A$). The SI unit is W m^{-2}. Note that $E = \int E_\lambda d\lambda$, where E_λ is the spectral irradiance at wavelength λ. For a parallel and perpendicularly incident beam not scattered or reflected by the target or its surroundings fluence rate (E_o) is an equivalent term. See also spectral irradiance.

Isoniazid (INH)

A first-line, oral drug used either alone as preventive therapy or in combination with several other drugs to treat TB disease.

Laminar flow

HEPA filtered air that is blown into a room at a rate of 30 m ±3 m / min (90 ±10 feet/min) in a unidirectional pattern with 100 ACH - 400 ACH.

M. tuberculosis complex

A group of closely related mycobacterial species that can cause active TB (e.g., M. tuberculosis, M. bovis, and M. africanum); most TB in the United States is caused by M. tuberculosis.

Multidrug-resistant tuberculosis (MDR - TB)

Active TB caused by M. tuberculosis organisms that are resistant to more than one anti-TB drug; in practice, often refers to organisms that are resistant to both INH and rifampin with or without resistance to other drugs (see Drug resistance, acquired and Drug resistance, primary).

Natural ventilation

The movement of outdoor air into a space through intentionally provided openings (i.e., windows, doors, nonpowered ventilators).

Negative pressure

The relative air pressure difference between two areas in a health-care facility. A room that is at negative pressure has a lower pressure than adjacent areas, which keeps air from flowing out of the room and into adjacent rooms or areas.

Nonmelanoma skin cancer (NMSC) (see the US National Cancer Institute's Online Cancer Dictionary)

Skin cancer that arises in basal cells or squamous cells but not in melanocytes (pigment-producing cells of the skin).

Nosocomial

An occurrence, usually an infection, that is acquired in a hospital or as a result of medical care.

Outdoor air

Air taken from the external atmosphere and, therefore, not previously circulated through the system.

Optical radiation [see ILV 845- 01-02 (CIE, 1987)]

Electromagnetic radiation at wavelengths between the region of transition to X-rays ($\lambda \approx$ 1 nm) and the region of transition to radio waves ($\lambda \approx$ 1 mm).

Particulate matter (particles)

A state of matter in which solid or liquid substances exist in the form of aggregated molecules or particles. Airborne particulate matter is typically in the size range of 0,01 μm – 100 μm diameter.

Photokeratitis [see CIE S009:2002 (CIE, 2002)]

Defined in CIE 106/2 (Photokeratitis, reprint of CIE-Journal, Vol.5/1, pp.19-23, 1986) as: an inflammation of the cornea, following over-exposure to ultraviolet radiation.

Photoconjunctivitis [see CIE S009:2002 (CIE, 2002)]

Defined in CIE 106/3 (Photoconjunctivitis, reprint of CIE-Journal, Vol.5/1, pp.24-28, 1986) as: a painful inflammation of the conjunctiva, may come about by accidental exposure of the eye to ultraviolet radiation.

Photokeratoconjunctivitis [see CIE S009:2002 (CIE, 2002)]

Inflammatory response of the cornea and conjunctiva following exposure to ultraviolet (UV) radiation. Wavelengths shorter than 320 nm are most effective in causing this condition. The peak of the action spectrum is approximately at 270 nm.

Note: Different action spectra have been published for photokeratitis and photoconjuctivitis [CIE 106/2 and CIE 106/3–1993 (CIE, 1993)]; however, the latest studies support the use of a single action spectrum for both ocular effects [CIE 106/1–1993 (CIE, 1993)].

Photon

The quantum of electromagnetic energy at a given frequency. This energy ($E = h\nu$) is the product of Planck's constant (h) and the frequency of the radiation (ν).

Photoreactivation

The enzyme-mediated reversal of the biological effects of UV-C or UV-B radiation mediated by radiation of longer wavelength and associated with the reversion of cyclobutane-type pyrimidine dimers to monomeric pyrimidines.

Positive pressure

Air pressure differential between two adjacent air spaces such that airflow is directed from the room relative to the corridor ventilation (i.e., air from corridors, adjacent areas is prevented from entering the room).

Radiance (in a given direction, at a given point of a real or imaginary surface) **(L_e; L)** [see ILV 845- 01-34 (CIE, 1987)]

Quantity defined by the formula $L_e = \frac{d\Phi_e}{dA \cdot \cos\theta \cdot d\Omega}$, where $d\Phi_e$ is the radiant flux transmitted by an elementary beam passing through the given point and propagating in the solid angle $d\Omega$ containing the given direction; dA is the area of a section of that beam containing the given point; θ is the angle between the normal to that section and the direction of the beam.

unit: $W \cdot m^{-2} \cdot sr^{-1}$

Notes 1 to 5.

In the five following notes the symbols for the quantities are without subscripts because the formulas are also valid for the terms 845-01-35 and 36.

1. For an area dA of the surface of a source, since the intensity dI of dA in the given direction is dI = dΦ / dΩ, then an equivalent formula is $L = \frac{\mathrm{d}I}{\mathrm{d}A \cdot \cos\theta}$, a form mostly used in illuminating engineering.

2. For an area dA of a surface receiving the beam, since the irradiance or illuminance dE produced by the beam on dA is dE = dΦ / dA, then an equivalent formula is $L = \frac{\mathrm{d}E}{\mathrm{d}\Omega \cdot \cos\theta}$, a form useful when the source has no surface (e.g. the sky, the plasma of a discharge).

3. Making use of the geometric extent dG of the elementary beam, since dG = dA · cos θ · dΩ, then an equivalent formula is L = dΦ/dG.

4. Since the optical extent $G \cdot n^2$ (see Note to 845-01-33) is invariant, then the quantity $L \cdot n^{-2}$ is also invariant along the path of the beam if the losses by absorption, reflection and diffusion are taken as zero. That quantity is called the **basic radiance** or **basic luminance** or **basic photon radiance**.

5. The relation between dΦ and L given in the formulae above is sometimes called basic law of radiometry and photometry:

$$\mathrm{d}\Phi = L\frac{\mathrm{d}A \cdot \cos\theta \cdot \mathrm{d}A' \cdot \cos\theta'}{l^2} = L \cdot \mathrm{d}A \cdot \cos\theta \cdot \mathrm{d}\Omega = L \cdot \mathrm{d}A' \cdot \cos\theta' \cdot \mathrm{d}\Omega'$$

with the notation given here and at 845-01-33.

Further explanation: For a parallel beam it is the radiant power, Φ_e, of all wavelengths leaving or passing through an infinitesimal element of surface in a given direction from the source divided by the orthogonally projected area of the element in a plane normal to the given direction of the beam, θ, [(dΦ_e/dA)/ cos θ, simplified expression: $L = \Phi_e/(A \cos\theta)$ when the radiant power is constant over the surface area considered]. The SI unit is W · m^{-2}. Note that $L = \int L_\lambda \mathrm{d}\lambda$, where L_λ is the spectral radiance at wavelength λ.

Radiant energy (Q_e; Q) [see ILV 845- 01-27 (CIE, 1987)]

Time integral of the radiant flux Φ_e over a given duration Δt.

$$Q_e = \int_{\Delta t} \Phi_e \mathrm{d}t$$

unit: J = W · s

Further explanation: In other words, the total energy emitted, transferred or received as radiation of all wavelengths in a defined period of time *(*$Q_e = \int Q_\lambda \mathrm{d}\lambda$). It is the product of radiant power*,* Φ_e*,* and time, *t:* $Q_e = \Phi_e t$ when the radiant power is constant over the time considered. The SI unit is J.

Radiant (energy) flux (Φ_e)

Although flux is generally used in the sense of the “rate of transfer of fluid, particles or energy across a given surface”, the radiant energy flux has been adopted by IUPAC as equivalent to radiant power, Φ_e. (Φ_e= dQ_e/dt, simplified expression: $\Phi_e = Q_e/t$ when the radiant energy, Q_e, is constant over the time considered.)

Radiant exposure (at a point of a surface, for a given duration) **(H_e; H)** [see ILV 845- 01-42 (CIE, 1987)]

Quotient of dQ_e, radiant energy incident on an element of the surface containing the point over the given duration, by the area of that element.

Equivalent definition: Time integral of E_e, irradiance at the given point, over the given duration Δt.

$$H_e = \frac{dQ_e}{dA} = \int_{\Delta t} E_e \cdot dt$$

unit: $J \cdot m^{-2} = W \cdot s \cdot m^{-2}$

Note: The quantity *exposure* here defined must not be confused with the quantity also named exposure which is used in the field of X and γ rays, the unit of which is coulomb per kilogram ($C \cdot kg^{-1}$).

Further explanation: When the radiant energy delivered to a given area (J/m^2) is constant over the area then the radiant exposure is Q_e/A.

When the irradiance is constant over the time considered then $H = E \cdot t$. For a parallel and perpendicularly incident beam not scattered or reflected by the target or its surroundings fluence $(H_{e,o})$ is an equivalent term.

Radiant flux; radiant power (Φ_e; Φ; P) [see ILV 845- 01-24 (CIE, 1987)]

Power emitted, transmitted or received in the form of radiation.

unit: W

See radiant power.

Radiant intensity (of a source in a given direction) **(I_e; I)** [see ILV 845-01-30 (CIE, 1987)]

Quotient of the radiant flux $d\Phi_e$ leaving the source and propagated in the element of solid angle $d\Omega$ containing the given direction, by the element of solid angle.

$$I_e = \frac{dQ_e}{d\Omega}$$

unit: $W \cdot sr^{-1}$

Further explanation: $I = \Phi_e/\Omega$ when the radiant power is constant over the solid angle considered. Note that $I = \int I_\lambda \, d\lambda$, where I_λ is the spectral radiant intensity at wavelength λ.

Radiant power (Φ_e; Φ; P)

Same as radiant (energy) flux. Power emitted, transferred or received as radiation. The SI unit is $J \cdot s^{-1} = W$.

Radiant spherical exposure; radiant fluence (at a point, for a given duration) **($H_{e,o}$; H_o)** [see ILV 845-01-45 (CIE, 1987)]

Time integral of the spherical irradiance $E_{e,o}$ at the given point over the given duration Δt.

$$H_{e,0} = \int_{\Delta t} E_{e,o} \cdot dt$$

unit: $J \cdot m^{-2} = W \cdot s \cdot m^{-2}$

Note: The analogous quantities luminous spherical exposure $H_{v,o}$ and photon spherical exposure $H_{p,o}$ are defined in a similar way, replacing spherical irradiance $E_{e,o}$ by spherical illuminance $E_{v,o}$ or photon spherical irradiance $E_{p,o}$.

Radiometer [see ILV 845- 05-06 (CIE, 1987)]

Instrument for measuring radiometric quantities.

Recirculation

Ventilation in which all or most of the air that is exhausted from an area is returned to the same area or other areas of the facility.

Relative humidity

The ratio of the amount of water vapor in the atmosphere to the amount necessary for saturation at the same temperature. Relative humidity is expressed in terms of percent and measures the percentage of saturation. At 100% relative humidity, the air is saturated. The relative humidity decreases when the temperature is increased without changing the amount of moisture in the air.

Respirable particles

Those particles that penetrate into and are deposited in the nonciliated portion of the lung. Particles > 10 μm in diameter are not respirable.

Return air

Air removed from a space to be then recirculated or exhausted.

Room-air HEPA recirculation systems and units

Devices (either fixed or portable) that remove airborne contaminants by recirculating air through a HEPA filter.

Single-pass ventilation

Ventilation in which 100% of the air supplied to an area is exhausted to the outside.

Spherical irradiance (at a point) **($E_{e,o}$; E_o)**; **radiant fluence rate** [see ILV 845- 01-40 (CIE, 1987)]

Quantity defined by the formula $E_{e,o} = \int_{4\pi sr} L_e d\Omega$ where $d\Omega$ is the solid angle of each elementary beam passing through the given point and L_e its radiance at that point.

unit: $W \cdot m^{-2}$

Notes.

1. - This quantity is the quotient of the radiant flux of all the 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.

2. - The analogous quantities spherical illuminance $E_{v,o}$ and photon spherical irradiance $E_{p,o}$ are defined in a similar way, replacing radiance L_e by luminance L_v or photon radiance L_p.

3. - The term “spherical irradiance”, or scalar irradiance, or similar terms may be found in the literature, in the definition of which the area of the cross-section is sometimes replaced by the surface area of the spherical element which is four times larger.

Source case

A case is an infectious person who has transmitted an infectious particle to another person or persons.

Source control

Controlling a contaminant at the source of its generation, which prevents the spread of the contaminant to the general work space.

Spectral irradiance (E_λ)

Irradiance, E, at wavelength λ per unit wavelength interval. The SI unit is $W \cdot m^{-3}$, but a commonly used unit is $W \cdot m^{-2}\ nm^{-1}$.

Squamous cell carcinoma (SCC) (see the US National Cancer Institute's Online Cancer Dictionary)

Cancer that begins in squamous cells, which are thin, flat cells that look like fish scales. Squamous cells are found in the tissue that forms the surface of the skin, the lining of the hollow organs of the body, and the passages of the respiratory and digestive tracts. Also called epidermoid carcinoma.

Sterilization

The use of a physical or chemical procedure to destroy all microbial life, including large numbers of highly resistant bacterial endospores.

Supply air

Air delivered to the conditioned space and used for ventilation, heating, cooling, humidification, or dehumidification.

TB infection

A condition in which living tubercle bacilli are present in the body but the disease is not clinically active. Infected persons usually have positive tuberculin reactions. but they have no symptoms related to the infection and are not infectious. However, infected persons remain at lifelong risk for developing disease unless preventive therapy is given.

TLV - TWA - Threshold Limit Value

Time Weighted Average: the time-weighted average concentration for a normal 8-hour workday and a 40-hour workweek to which nearly all workers may be exposed repeatedly, day after day, without adverse effects.

TLV Threshold Limit Value

An exposure level under which most people can work consistently for 8 hours a day, day after day, without adverse effects. Used by the ACGIH to designate degree of exposure to contaminants. TLV can be expressed as approximate milligrams of particulate per cubic meter of air (mg/m^3). TLVs are listed as either an 8-hour as a TWA (time weighted average) or a 15-minute STEL (short term exposure limit).

Transmission

The spread of an infectious agent from one person to another. The likelihood of transmission is directly related to the duration and intensity of exposure to M. tuberculosis (see exposure).

Tubercle bacilli

M. tuberculosis organisms.

Tuberculosis (TB)

A clinically active, symptomatic infectious disease caused by an organism in the Mycobacteria tuberculosis complex.

TWA - Time Weighted Average

Average exposure for an individual over a given working period, as determined by sampling at given times during the period. TWA is usually presented as the average concentration over an 8-hour workday for a 40-hour workweek.

Ultraviolet radiation [see ILV 845- 01-05 (CIE, 1987)]

Optical radiation for which the wavelengths are shorter than those for visible radiation.

Note. - For ultraviolet radiation, the range between 100 nm and 400 nm is commonly subdivided into:

UV-A 315 ..... 400 nm
UV-B 280 ..... 315 nm
UV-C 100 ..... 280 nm

Ultraviolet germicidal irradiation (UVGI)

The use of ultraviolet radiation to kill or inactivate microorganisms. UVGI is generated by germicidal lamps that kill or inactivate microorganisms by emitting ultraviolet germicidal radiation, predominantly at a wavelength of 253,7 nm.

Vegetative bacteria

Bacteria which are actively growing and metabolizing, as opposed to a bacterial state of quiescence which is achieved when certain bacteria (i.e., gram-positive bacilli) convert to spores when the environment can no longer support active growth.

Ventilation

The process of supplying and removing air by natural or mechanical means to and from any space. Such air may or may not be conditioned. Used as an engineering control technique to dilute and remove airborne contaminants by the flow of air into and out of an area. Air that contains droplet nuclei is removed and replaced by contaminant-free air. Droplet nuclei and infectious particles become dispersed and their concentration in the air is diluted.

Ventilation air

That portion of the supply air that is outdoor air plus any recirculated air that has been treated for the purpose of maintaining acceptable indoor air quality.

Ventilation, dilution

An engineering control technique to dilute and remove airborne contaminants by the flow of air into and out of an area. Air that contains droplet nuclei is removed and replaced by contaminant-free air. If the flow is sufficient, droplet nuclei become dispersed, and their concentration in the air is diminished.

Ventilation, local exhaust

Ventilation used to capture and remove airborne contaminants by enclosing the contaminant source (i.e., the patient) or by placing an exhaust hood close to the contaminant source.

Virulence

The degree of pathogenicity of a microorganism as indicated by the severity of the disease produced and its ability to invade the tissues of a host. M. tuberculosis is a virulent organism.

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