



Chapter 1

Introduction

1.1 Ultraviolet Germicidal Irradiation (UVGI)

Ultraviolet germicidal irradiation (UVGI) is defined as the use of ultraviolet (UV) wavelengths of light in the germicidal range (200–320 nm) for the disinfection of air and surfaces. The term ‘UVGI’ was originally coined by the International Commission on Illumination (CIE) and adopted later by the Centers for Disease Control (CDC), and this term distinguishes disinfection applications from the non-germicidal UVA wavelengths of black lights and tanning lamps (320–400 nm). UVGI is also used to distinguish air and surface disinfection applications from those in water (CIE 2003). Throughout this book the terms ‘UVGI’ and ‘UV’ will be used interchangeably, with the understanding that in every context, unless otherwise noted, both terms refer to the germicidal wavelengths of UVC (200–280 nm) and UVB (280–320 nm). UV radiation below 320 nm is actinic, which means it causes photochemical reactions. UVA radiation (320–400 nm) is not considered germicidal and is not specifically addressed in this book (except in relation to pulsed light). Table 1.1 summarizes the definitions of the primary bands of UV radiation. Previously, UVA was considered to extend down to 315 nm, but the range 315–320 nm was found to have some minor germicidal effects. The UVA band, and therefore the UVB band also, have been redefined by various organizations such that all actinic UV radiation is now contained strictly within the UVB and UVC range. This division allows UVA to be completely non-germicidal and conveniently places all the germicidal UV into the UVB and UVC bands.

The definitions of the UV bands UVA, UVB, and UVC given in Table 1.1 have not yet been fully incorporated into every relevant guideline or adopted by every agency, but are likely to be adopted eventually and universally. VUV (Vacuum Ultraviolet) does not transmit through air since it is rapidly absorbed and therefore the VUV band is of no interest in air and surface disinfection, and is not addressed further in this book.

This introductory chapter presents some other basic definitions and subjects which provide a background for the subsequent chapters, where these concepts

Table 1.1 Primary bands of ultraviolet radiation

Band	Wavelength, nm	Type and classification		
UVA	320–400	Non-germicidal (Near-UV, Blacklight)		
UVB	280–320	Erythematous	Germicidal	Actinic
UVC	200–280	Ozone-producing		
VUV	100–200	Vacuum ultraviolet		

will be addressed in greater detail. The chapters in this book are arranged to first address the background information, including theory and mathematical modeling, then equipment and design methods, and finally testing and applications. In the Appendices are provided tabulations of data and information that are useful and that will be referenced throughout this book.

1.2 Brief History of Ultraviolet Disinfection

The story of ultraviolet light begins with Isaac Newton and his contemporaries. In 1672, Isaac Newton published a series of experiments with prisms that resolved sunlight into its constituents colors, red through violet. The effects of sunlight on man, microorganisms, and chemicals became a matter of great interest and experimentation in the 1800s. In 1814, Fraunhofer mapped over 500 bands of sunlight, some of which were in the ultraviolet region. In 1842, Becquerel and Draper each independently showed that wavelengths between 340 and 400 nm induced photochemical changes on daguerreotype plates (Hockberger 2002).

UV Lamp development predates sunlight studies on bacteria. In 1835, Wheatstone invented the first mercury (Hg) vapor arc lamp, but it was unstable and short-lived. Fizeau and Foucault (1843) reported problems with their eyes after experimenting with a carbon arc lamp, and speculated that it was due to ‘chemical rays.’ In 1850, Stokes used aluminum electrodes to produce a ‘closed’ arc lamp in a quartz tube that emitted UV rays to 185 nm (Hockberger 2002).

The earliest scientific observations of the germicidal effects of ultraviolet radiation began with Downes and Blunt (1877) who reported that bacteria were inactivated by sunlight, and found that the violet-blue spectrum was the most effective. In 1885, Arloing and Duclaux demonstrated that sunlight had a killing effect on *Bacillus anthracis* and *Tyrophrix scaber*, respectively. Widmark (1889, 1889a) published studies confirming that UV rays from arc lamps were responsible for skin burns, using a prism to separate the UV spectrum and water to block the infrared rays. It was demonstrated in 1892 that ultraviolet light was responsible for this action with tests on *Bacillus anthracis* (Ward 1892). Also in 1892, Geisler used a prism and a heliostat to show that sunlight and electric arc lamps were lethal to *Bacillus typhosus*. Finsen (1900) performed the first rigorous analysis of the effects of UV light. The UV spectrum around 250 was identified as biocidal by Barnard and Morgan (1903), and the range was narrowed by Newcomer (1917), and isolated to

253.7 nm by Ehrismann and Noethling (1932). Table 1.2 summarizes most of the critical developments in the history of UV research and applications.

The first use of UV to disinfect drinking water is said to have been in 1906 according to von Recklinghausen (1914). In 1909/1910 the first water disinfection

Table 1.2 Chronology of critical events in UV history

Year	Event	Reference
1814	Fraunhofer maps spectral bands of sunlight	Hockberger (2002)
1835	Wheatstone invents first mercury vapor arc lamp	Hockberger (2002)
1850	Stokes invents quartz arc lamp that produces to 185 nm	Hockberger (2002)
1842	Becquerel and Draper find 340–400 nm light photoreactive	Hockberger (2002)
1877	Bactericidal effects of sunlight first demonstrated	Downes and Blunt (1877)
1889	UV light demonstrated to be erythematous	Widmark (1889)
1892	UV component of sunlight identified as biocidal	Ward (1892)
1892	Geissler demonstrates lethality of arc lamps to <i>B. typhosus</i>	Hockberger (2002)
1903	UV spectrum from 226 to 328 nm found to be germicidal	Barnard and Morgan (1903)
1904	First quartz lamp for UV developed	Lorch (1987)
1906	UV first used to disinfect drinking water	von Recklinghausen (1914)
1909	First European applications for UV water disinfection	AWWA (1971)
1912	Henri found shorter UV wavelengths don't penetrate	Henri (1912)
1916	First USA applications of UV for water disinfection	AWWA (1971)
1921	UV photoreactivity with TiO ₂ first demonstrated	Renz (1921)
1925	UV photodegradation of materials first demonstrated	Luckiesh and Taylor (1925)
1927	First erythematous action spectrum published	Hausser and Vahle (1927)
1927	Bactericidal action of UV first quantified scientifically	Bedford 1927, Gates (1929)
1928	Virucidal action of UV first quantified scientifically	Rivers and Gates (1928)
1929	Fungicidal action of UV first quantified scientifically	Fulton and Coblenz (1929)
1932	UV germicidal peak at 253.7 nm isolated	Ehrismann and Noethling (1932)
1932	Erythematous spectrum of UV first quantified	Coblenz et al. (1932)
1936	First overhead UV system in hospitals	Wells and Wells (1936), Hart (1936)
1936	UV photoreactivation phenomena first identified	Prat (1936)

Table 1.2 (continued)

Year	Event	Reference
1937	First upper air application in schools	Wells (1938)
1938	First fluorescent gas discharge UV lamp	Whitby and Scheible (2004)
1940	UV first applied to air conditioning systems	Rentschler and Nagy (1940)
1942	First UV air disinfection sizing guidelines	Luckiesh and Holladay (1942)
1942	Upper and lower UV applied to Army/Navy barracks	Wells et al. (1942)
1950	First catalog sizing methods	Buttolph and Haynes (1950)
1954	First air conditioner application	Harstad et al. (1954)
1954	Faulty British study concludes UV is ineffective	MRC (1954)
1957	Riley proves effectiveness of UV for TB control	Riley et al. (1957)
1974	First microbial growth control systems	Grun and Pitz (1974)
1985	Cooling coil UV systems in use in European breweries	Philips (1985)
1994	CDC acknowledges UV effectiveness for TB control	CDC (2005)
1996	First cooling coil irradiation system in US	Scheir (2000)
1997	First UV light emitting diodes (LEDs) at 265 nm	Guha and Bojarczuk (1998)
1999	WHO recommends UVGI for TB control	WHO (1999)
2000	US army recommends UVGI for disease isolation	USACE (2000)
2003	CDC formally sanctions UVGI use in hospitals	CDC (2003)
2003	FEMA sanctions UVGI as a biodefense option for buildings	FEMA (2003)
2003	First in-duct UVGI system demonstrated to reduce illness symptoms and airborne contamination	Menzies et al. (2003)
2003	ASHRAE forms UV air and surface treatment committee	Martin et al. (2008)
2005	Federal government specifies UV for cooling coil disinfection	GSA (2003)
2007	Overhead UV system proven to reduce SSIs in ORs	Ritter et al. (2007)

system was operated at Marseilles, France. The first evidence that UV light produced photochemical effects on microorganisms was presented by Henri (1914). In 1916 the first US system for water disinfection was tested at Henderson, KY (AWWA 1971). In 1921, Renz demonstrated that UV could cause photoreactions with titanium oxide (TiO₂). Hausser and Vahle (1927) produced the first detailed action spectrum for erythema. Bedford (1927) and Gates (1929) were among the first to establish UV dosages necessary for bacterial disinfection. Fungal disinfection dosages were first published by Fulton and Coblenz (1929). The first studies on UV irradiation of viruses appear to have been those published by

Rivers and Gates (1928) and Sturm et al. (1932). Coblentz et al. (1932) refined the erythral action spectrum.

The 1930s saw the first applications of UV systems in hospitals to control infections (Wells and Wells 1936, Hart and Sanger 1939, Robertson et al. 1939, Kraissl et al. 1940, Overholt and Betts 1940). The first Upper Room UV systems appear to be those installed by Wells (1938). In the 1940s the first detailed design and analysis of UV air disinfection were published along with basic guidelines for applying UV in ventilation systems (Rentschler and Nagy 1940, Sharp 1940, Wells 1940, Buchbinder and Phelps 1941, DelMundo and McKhann 1941, Luckiesh and Holladay 1942, Sommer and Stokes 1942, Henle et al. 1942, Hollaender 1943). The first attempts to use UV systems to control respiratory infections in schools and barracks occurred shortly thereafter (Wells et al. 1942, Wells 1943, Schneiter et al. 1944, Wheeler et al. 1945, Perkins et al. 1947, Higgons and Hyde 1947). Several early attempts were made to develop rigorous sizing methods and engineering guidelines for UV applications (Luckiesh and Holladay 1942a, Luckiesh 1945, 1946).

By the 1950s it had been well-established that UV irradiation was effective at disinfecting both air and surfaces, and new engineering applications were being developed. General Electric catalogs detailed a wide variety of UV applications including various methods of installing UV lamps inside ducts and air conditioners (Buttolph and Haynes 1950, GE 1950). Harstad et al. (1954) demonstrated that installation of UV lamps in air conditioners would reduce airborne contamination, and that microorganisms were impinging upon and collecting on internal AHU surfaces. Bacterial growth on cooling coils had been recognized as a potential health problem as early as 1958 (Walter 1969). The first evidence that air cooling equipment could actually cause respiratory infections was presented by Anderson (1959) when an air cooling apparatus was found to be contaminated with microbial growth. This very same concern had been raised in hospital environments since about 1944 but the possibility of growth of bacteria on air-conditioning cooling coils wasn't conclusively demonstrated until 1964 (Cole et al. 1964). The growth of microbes on other equipment like filters and dust inside air-conditioning ducts was first demonstrated by Whyte (1968). The dissemination of microbes by ventilation systems and their potential to cause respiratory infections became widely recognized in the late 1960s in both the medical and engineering professions (Banaszak et al. 1970, Schicht 1972, Zeterberg 1973). It was understood at this time that microbial growth could occur anywhere that air came into contact with moisture (Gunderman 1980, Ager and Tickner 1983, Spendlove and Fannin 1983). The first UVGI system designed specifically for disinfecting the surfaces of air handling equipment, including humidifier water and filters, was detailed by Grun and Pitz (1974). Luciano (1977) detailed many applications of UVGI, including hospital applications in which the UV lamps are specifically placed upstream of the cooling coils and downstream of the filters. In 1985 Phillips published a design guide in which the first definitive description of applications of UV lamps for the control of microbial growth were presented (Phillips 1985). The Philips design guide mentions European installations that were already in operation prior to 1985. In January of 1996 the first UVGI system in the US designed for controlling

microbial growth on cooling coils was installed by Public Service of Omaha (PSO) in Tulsa (Scheir 2000). In the same year, the Central and Southwest Corporation followed the PSO example and began realizing considerable energy savings (ELP 2000).

Although UVGI systems had been in use in hospitals since 1936 but it wasn't until 2003, some sixty years later, that the CDC formally acknowledged that UV systems were effective and could be used in hospitals with one caveat – UV Upper Room and in-duct systems could only be used to supplement other air cleaning systems (CDC 2003). In 1957, Riley and associates successfully completed a demonstration of how UV air disinfection could control the spread of tuberculosis (TB) in hospital wards (Riley et al. 1957). It wasn't until 1994, over forty years later, that the Centers for Disease Control (CDC) acknowledged that UV could be effective for controlling TB, in response to the growing worldwide TB epidemic which had resisted control by traditional methods (CDC 2005). In 2003, The influential American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) formed a task group to focus on UV air and surface treatment (TG2.UVAS) which became the standing Technical Committee TC 2.9 in 2007 (Martin et al. 2008).

1.3 Units and Terminology

A variety of units have been used in UV disinfection for the irradiance and the UV dose. The irradiance, sometimes called intensity, has the preferred units of W/m^2 in air and surface disinfection. The UV dose (aka fluence rate) has the preferred units of J/m^2 in air and surface disinfection. Conversion factors for the various units that have been used in the literature are provided in Table 1.3. The use of Table 1.3 is straightforward as shown in the following examples. Note that a joule (J) is equivalent to a watt-second (W-s), and that a W/m^2 is equal to a $\mu W/mm^2$.

Example 1: Convert the irradiance 144 mW/cm^2 (milliwatts per square centimeter) to units of W/m^2 (watts per square meter)

Answer: Read downwards from the first column, mw/cm^2 to the gray box and then over to the second column, W/m^2 , where the conversion factor is seen to be 10. Multiply $144 \times 10 = 1440 \text{ W/m}^2$.

Example 2: Convert the UV dose $33 \mu J/cm^2$ (microJoules per square centimeter) to units of J/m^2 (Joules per square meter).

Answer: Read up from the fourth column, $\mu J/cm^2$, to the gray box, and then over to the second column, J/m^2 , where the conversion factor is seen to be 0.01. Multiply $33 \times 0.01 = 0.33 \text{ J/m}^2$.

The term 'UVC' is often used today to encompass all applications of germicidal UV but the correct definition of this term is, of course, the band of UV wavelengths between 200 and 280 nm, and this strict definition is the one used throughout this book. For example, a UV lamp could refer to any lamp that produces any UV wavelengths, including black light and suntan lamps (although in this book only

Table 1.3 Units of Irradiance and UV Dose

Conversion factors for irradiance (Read down from units to gray block and then horizontally for unit equivalence.)					
mW/cm ²	W/m ²	erg/mm ² -s	μW/cm ²	erg/cm ² -s	W/ft ²
	μW/mm ²				
	J/m ² -s				
1	10	100	1000	10000	1.07639
0.1	1	10	100	1000	0.107639
0.01	0.1	1	10	100	0.010764
0.001	0.01	0.1	1	10	0.001076
0.0001	0.001	0.01	0.1	1	0.000108
0.929	9.29	92.90	929.0	9290	1
mJ/cm ²	μW-s/mm ²	erg/mm ²	μJ/cm ²	erg/cm ²	W-s/ft ²
	W-s/m ²		μW-s/cm ²		
mW-s/cm ²	J/m ²				

Conversion factors for UV Dose (Exposure time = 1 second) (Read up from units to gray block and then horizontally for unit equivalence.)					
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germicidal UV lamps are addressed). The term ‘UVGI lamp’ specifically refers to lamps that produce UV wavelengths in the actinic ‘broad-band’ range between 200 and 320 nm (excluding black lights and sunlamps). The term ‘UVC lamp’ specifically refers to lamps that produce UVC wavelengths in the ‘narrow-band’ range 200–280 nm. In current and common usage, the term ‘UVC’ often implies that the UVC band is the only contributor to the germicidal effect, but this implication is often incorrect and such usage is avoided in this text – wherever the term ‘UVC’ is used herein it refers specifically to the UVC band of radiation. Other terms such as UVR (ultraviolet radiation) and GUV (germicidal ultraviolet) have also been used in a germicidal context in the past.

The term ‘germicidal’ implies that these UV systems destroy, kill, or inactivate microorganisms such as viruses, bacteria, and fungi. Technically, viruses are molecules, and so it customary to refer to viruses as being inactivated rather than killed. In all cases, germicidal action means disinfection, and disinfection implies a reduction in the microbial population, whether in air, water, or on surfaces. Microbial populations are measured in terms of cfu, or colony-forming units (i.e. grown on petri dishes). In the case of viruses, the appropriate measure of viral populations is pfu, or plaque-forming units. However, wherever the term ‘cfu’ is used in this book, it will be considered to apply to both viruses and bacteria (as a matter of convenience), with the reader’s understanding that the correct terminology for viruses is pfu, whether it is used or not. The density of microbes in air is always given in units of cfu/m³ (although some older texts use cfu/ft³). The density of microbes on surfaces is given in cfu/cm² (in older texts it is cfu/in²). The disinfection of air will therefore be measured in terms of a reduction in the airborne density in cfu/m³, and the disinfection of surfaces is measured in terms of the reduction of cfu/cm².

Sterilization is a related term that implies the complete elimination of a microbial population. It is difficult, however, to actually demonstrate the complete elimination of a microbial population since any microbiological test will have some limit of

accuracy. As a practical convenience in air disinfection applications, and for analytical purposes, ‘mathematical sterilization’ can be assumed to represent a disinfection rate of six logs or better, when there are no survivors. This definition may not apply to water UV disinfection, but in air disinfection applications it would be most unusual to have airborne densities on the order of a million cfu/m³, and typical airborne densities are in the range of a few thousand cfu/m³. Obviously, with densities of a few thousand cfu/m³, a three or four log reduction (1000–10,000 cfu/m³) would result in sterilization, and a six log reduction is an adequate definition of sterilization for air disinfection applications. Surface disinfection is another matter altogether and the densities of surface contamination are neither well understood nor well defined, and so the ‘mathematical definition’ of sterilization for surface disinfection is left undefined in this text.

1.4 Air vs. Water Disinfection

The design of UV systems for water disinfection differs from that of air and surface disinfection applications and therefore the cumulative knowledge accrued in the water industry is of limited direct use for air and surface disinfection applications. UV rays are attenuated in water and this process has no parallel in air disinfection, even with saturated air. The attenuation of UV irradiance in water occurs within about 15 cm and this necessitates both higher UV power levels and closely packed arrays of UV lamps. The estimates of UV doses required for water disinfection are on the order of ten times higher than those needed in air disinfection applications, and this difference distorts any attempt to use water UV system sizing methods to design air disinfection systems. Furthermore, the array of particular microorganisms of concern in the water industry differs considerably from those found in air and therefore water-based UV rate constants are of use only where the microbial agent is both airborne and waterborne (i.e. *Legionella*), or is also surface-borne, and for theoretical analysis. Some overlap in waterside and airside UV applications also exists in the area of foodborne pathogens, where certain foodborne pathogens may become airborne, and where they may exist as surface contamination amenable to UV disinfection.

Although the UV exposure dose in air is a simple function of airflow and exposure time, and the UV irradiance field in air is not too difficult to define, the susceptibility of airborne microbes is a complex function of relative humidity and species-dependent response. It has often been thought that the UV susceptibility of microbes in air at 100% relative humidity (RH) should correspond to their susceptibility in water, but this proves to be overly simplistic and it can only be said that UV susceptibility at high RH approaches that in water. As a result of these various differences between water-based UV disinfection and UVGI air and surface disinfection, research into the former provides limited benefits to research into air-based disinfection, and the subject of water disinfection is not addressed in this book except insofar as it has some specific impact on air and surface disinfection and in the matter of their common theoretical aspects. The UV rate constant

database in the Appendices, addresses all known UV studies on microbial disinfection, including those for waterborne and foodborne pathogens and allergens. There are a wide variety of detailed texts on the subject of water disinfection with UV (many times more than for airside UV disinfection) and readers who wish to familiarize themselves with waterside UV technology and methods should consult these texts directly (see for example, Bolton and Cotton 2008). However, the information provided herein on UVGI theory and UV inactivation rate constants may be of no little interest to those involved in water disinfection.

1.5 Surface Disinfection

Surface disinfection refers to either the disinfection of building and ventilation system internal surfaces, or the disinfection of equipment and material surfaces, such as dental and medical equipment. Like water systems, surface UV disinfection systems have a long history of success. The design and operation of surface UV systems, however, have much more in common with air disinfection than do water systems. Contaminated surfaces are often a source of airborne microbes, and airborne microbes often produce surface contamination. The interaction of air and surface contamination processes makes the issue of air vs. surface disinfection almost inseparable for some applications, such as in the health care industry and the food industry. The disinfection of cooling coil surfaces, for example, removes mold spores from the coils and prevents subsequent aerosolization, thereby helping keep the air clean. UV systems for coil disinfection applications also disinfect the air directly and so such systems often perform simultaneous air and surface disinfection functions.

One of the main differences between air and surface disinfection with UV is that the relevant UV rate constants differ under these two types of exposure – airborne rate constants tend to be higher in air, under normal humidity. That is, microbes are more vulnerable in air, whereas microbes on surfaces appear to have a certain degree of inherent protection. Although the matter remains to be resolved by future research, the available database for UV rate constants for microbes on surfaces is useful as a conservative estimate of airborne rate constants, as are water-based rate constants, whenever airborne rate constant studies do not exist.

Since airborne microbes are often surface-borne, and vice-versa, and for the various reasons mentioned above, the overlap between these topics, air and surface UV disinfection, is extensive. In fact, the subject of surface disinfection has considerably more in common with air disinfection than water disinfection and often the two technologies are inter-related. It is appropriate, therefore to treat air and surface UV disinfection together, as in this text, and it should be understood that most air disinfection systems will simultaneously perform some surface disinfection function, intentionally or otherwise. Similarly, many UV surface disinfection systems (i.e. Lower Room systems, Overhead Surgical systems) will also perform some air disinfection functions, by design or otherwise.

1.6 Air Disinfection

Airborne pathogens and allergens present a much greater threat to human health than water-based microbes, in terms of total incidence and net costs of health care, but there are far fewer air disinfection systems in place than water disinfection systems, and much less information is available for airborne UV disinfection than for water applications. The success of UVGI for air disinfection application has also been subject to much interpretation and even outright dismissal, in spite of repeated demonstrations of its effectiveness. After decades of research, the field of airborne UV disinfection remains fraught with unknowns and misconceptions, and applications are far less numerous than they perhaps should be. The subsequent chapters attempt to consolidate the entire knowledge base relevant to UVGI and to demonstrate how the careful application of proper design principles and new approaches can produce results as predictable and reliable as those of water disinfection systems. New computational methods, combined with a wealth of recent design and installation experience and ongoing research, now allows systems to be installed with fairly high levels of confidence in terms of their performance.

Methods for demonstrating in-place performance, along with various guidelines and standards for such installations, have brought the field of UVGI from an uncertain art to a nearly complete science. The key missing component at this time is conclusive evidence that UVGI air disinfection reduces the incidence of airborne disease, a matter that will require years of data collection, once there are sufficient and adequate installations available for monitoring. Some current studies are exploring this avenue of research and preliminary results suggest that UVGI is, as theory and analysis predicts, effective in reducing both the symptoms and incidence of various airborne diseases. As applications increase, this database should eventually provide reliable evidence that may lead to full economic justification of UVGI installations in health care facilities, schools, and other types of buildings. The widespread use of UV for air disinfection in buildings is likely an eventuality that will pay economic and health dividends to future generations.

1.7 Air Disinfection Field Studies

The use of UV to disinfect air goes back some eighty years, and yet applications are still far from being common in modern buildings. Although nine out of ten UVGI field studies had positive results, the few that did not meet grand expectations were cited most often as proof of failure. In 1936 Hart used an array of UV lamps to sterilize supply air in a surgical operating room (Hart 1937). In 1937 the first installation of UV lamps in a school ventilation system dramatically reduced the incidence of measles, and subsequent applications enjoyed similar successes (Riley 1972). In the late 1940s, Wells and his associates installed UV systems across entire communities and demonstrated reductions in community disease transmission rates (Wells and Holla 1950). In the late 1950s experiments using guinea pigs demonstrated the elimination of tuberculosis (TB) bacilli from hospital ward exhaust air

(Riley and O'Grady 1961). A plethora of designs that were more imitative than engineered followed these early applications. The result was a mixture of successes and failures. In one poorly planned study by the MRC, investigators failed to achieve statistically significant reductions of disease and concluded erroneously that UV failed to reduce disease incidence (MRC 1954). The MRC study put a severe damper on further development of UV technology in the 1950s and 1960s, and as a result of this study being widely quoted (and in spite of it being widely criticized by experts), brought a near halt to further implementations and slowed research (Riley 1980, 1980a). This setback of the UV industry cannot be measured in terms of lost development, lost field data, lost health care costs, or lost lives, but there are those who today continue to insist that UVGI is an unproven 'snake oil' technology. We must convince them otherwise.

As a result of an apparently imperfect record of success, UVGI was widely ignored in various guidelines and standards, particularly in health care settings, where it should have been directly addressed. Without the sanction of the highest health authorities, UVGI languished and was largely ignored in health care settings where it would have done the most good. This checkered history is reflected in various guidelines that decline to mention the use of UVGI. Only a select few of the most well-informed hospitals and researchers took the time to investigate and adopt UV technologies, often with great success (Goldner and Allen 1973, Goldner et al. 1980, Nardell 1988). Recently, new research has reaffirmed what the original studies had always said, that UV technology can have a major impact on the reduction of various types of nosocomial and community-acquired infections (Menzies et al. 2003, Ritter et al. 2007, Escombe et al. 2009).

1.8 Pathogens and Allergens

Pathogens are any microbes that cause infections in humans and animals, and these include viruses, bacteria, and fungi. Some larger microbes, like protozoa, may also cause infections but these parasites are generally too large to be airborne. Therefore, this book primarily addresses only viruses, bacteria, and fungi, including bacterial spores and fungal spores, as air and surface contaminants. Insects, like dust mites, are not eradicable by UV and are not addressed in this text. All of the viruses listed in Appendix B are pathogens or bacteriophages, as are most of the bacteria in Appendix A and some of the fungi in Appendix C.

Allergens are microbes, biological products, and compounds that induce allergic reactions in atopic, or susceptible, individuals. Compounds and biological products (i.e. VOCs and pet dander) are generally not very susceptible to UV destruction (although they are easily removed by filters) and so they are not specifically addressed in this book. The allergens addressed in this book are strictly fungi and bacteria – there are no viral allergens. Some pathogens may also be allergens. Almost all of the fungi listed in Appendix C are allergens, and many of these are also pathogens. Almost all of the bacteria listed in Appendix A are pathogens, and some of these are also allergens.

Some bacteria, and virtually all fungi, can form spores. In the normal or growth state (called ‘vegetative’) bacteria exist as cells, and fungi exist as cells or yeast. Spore-forming (sporulating) bacteria and fungi will form spores under the right conditions (usually adverse conditions). Spores are dormant forms, usually more compact than the cell forms, round or ovoid shaped, and can resist heat, dehydration, and cold much better than the cell (or vegetative) form. They also tend to be resistant to UV exposure. Since they are typically smaller than the original cells, spores tend to become airborne easily and can be transported outdoors. Spores require only warmth, moisture, and shade to germinate, or return to a vegetative state, and require only nutrients to grow and multiply.

Some bacteria and fungi produce toxins, including endotoxins and exotoxins. UV has a limited effect on toxins but prolonged exposure can reduce toxin concentrations (Anderson et al. 2003, Asthana and Tuveson 1992, Shantha and Sreenivasa 1977). High levels of growth are required, usually under adverse conditions, for microbes to produce toxins, and since UV destroys toxin-producing bacteria and fungi, it is unlikely that sufficient levels of toxins will remain after UV disinfection to pose toxic hazards.

1.9 Current Research

In spite of the extensive research results available on UVGI air and surface disinfection, much work remains to be done. Recent studies have demonstrated the effectiveness of UVGI and have hinted at the possible reduction of airborne disease in commercial office buildings. The ability of UVGI to save costs in cooling coil maintenance has been fairly well established. There is also a need for more research to determine UV rate constants for a wider array of pathogens. Towards this end has been provided a guideline for laboratory testing (included in this book) that should facilitate the production of reproducible test results, something that has not always been the case in the past.

In addition to providing the most up-to-date information from current literature of UVGI, this text also provides the fruits of the author’s research into UV susceptibility, including a model for relative humidity effects in air, and a genomic model for predicting the UV susceptibility for viruses (addressed in Chaps. 2 and 4). Also presented here for the first time is the author’s research on pulsed UV light modeling.

Perhaps the most important applications of UVGI today is in the health care industry, which is in dire need of solutions to the problem of hospital-acquired (nosocomial) infections. Such infections have now spread outwards to become community-acquired infections and it is likely this pattern will keep repeating with new and emerging pathogens and drug-resistant strains until a more effective solution is implemented on a wide scale. UVGI can play a major role in limiting the spread of nosocomial infections but what is needed most is not new technology (adequate technology exists in the present) but encouragement and support in terms of guidelines and recommendations on UV technology from those authorities who have until recently been somewhat reticent and noncommittal on the matter.

1.10 UVGI and the Future of Disease Control

UVGI has a definite future in the control of contagious diseases and if applied on a widespread basis, it may be the key to controlling epidemics and pandemics. No other current technology has the capability, the adaptability, and the favorable economics to make it viable for an extremely wide variety of disease control applications. It is already used extensively and effectively in water applications and in surface disinfection applications. In combination with air filtration, it is the most effective and economic technology for disinfecting air. From health care applications to schools and residential environments, UVGI holds the promise of one day contributing in a major fashion to the eradication of many contagious diseases. The advent of multidrug-resistant microbes like MRSA and XTB, and emerging pathogens like SARS and Avian Influenza is likely to stimulate the increased use of UVGI systems in an ever wider number of applications. The contribution UV technology can make to the control of epidemics is amenable to analysis by the statistical models of epidemiology, which have demonstrated the potential for widespread use of UVGI systems to theoretically halt contagious airborne disease epidemics (Kowalski 2006). Perhaps continued research and development will ultimately lead to UVGI becoming a standard component of ventilation systems in all indoor environments and this age of airborne epidemics will come to an end.

References

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