

# **UVGI for Cooling Coil Disinfection and Air Treatment**

Report Prepared by Dr. Wladyslaw Kowalski, PE

The Penn State Indoor Environment Center

for

**American Air & Water, Inc.**

September 10<sup>th</sup>, 2006

TABLE OF CONTENTS

1. Executive Summary .....	3
2. Introduction and Background .....	4
3. Microbial Disinfection Model .....	7
4. Cooling Coil Disinfection .....	10
5. Performance of Cooling Coil Disinfection Systems .....	14
6. Economics of Cooling Coil Disinfection Systems .....	16
7. Guidelines for Cooling Coil Disinfection Systems .....	20
8. Hospital Air & Surface Disinfection Systems.....	21
9. Hotel Air & Surface Disinfection Systems .....	25
10. References and Bibliography .....	294
Appendix A: Microbial Rate Constants.....	42
Appendix B: Common Indoor Bacteria.....	47
Appendix C: Common Indoor Fungi .....	48
Appendix D: Health Care Facility Cost Estimates – Part 1 .....	49
Appendix E: Health Care Facility Cost Estimates – Part 2 .....	50
Appendix F: Excerpts from articles on UVC effectiveness .....	51

## **1. Executive Summary**

This report reviews the history and current literature on ultraviolet germicidal irradiation (UVGI) systems used for air and surface disinfection applications. Three of the most promising applications are addressed in this report:

- 1) Cooling Coil Disinfection
- 2) Hospital Air & Surface Disinfection
- 3) Hotel Air & Surface Disinfection

Cooling coil disinfection has proved to be a most economical application and can produce a payback in terms of energy savings of about two years or less. These savings result from reduced coil cleaning maintenance costs and energy savings due to improved heat transfer and reduced pressure losses from airflow through the coils. The use of UVGI on cooling coils tends to restore them to original design conditions and will maintain them in a clean state for as long as the UVGI system is operated. This report summarizes the available information on laboratory and field testing of such installations. Information on the energy savings and payback period of cooling coil irradiation are provided along with an example of the computation of a typical payback period. Draft guidelines on cooling coil irradiation systems from the International Ultraviolet Association are reviewed.

Applications in hospital or other health care facilities include cooling coil cleaning, medical equipment, surface disinfection in unoccupied areas, direct surgical site disinfection during procedures, and air disinfection in operating rooms, procedure rooms, delivery rooms, isolation rooms, patient wards, and general areas. The problem of hospital-acquired (nosocomial) infections is one that has never been brought under complete control, and that causes an undue number of fatal infections annually in the US, with concomitant economic costs. UVGI may be able to reduce many types of nosocomial infections, especially those that have an airborne route of transmission. This paper explores some of the various applications for air and surface disinfection that may assist hospitals in reducing nosocomial infection rates.

Hotels may obtain significant economic benefits both from the use of UVGI to keep cooling coils clean and from improvements in air quality, which will provide a better environment for both guests and employees. The kinds of problems encountered in large hotels that are amenable to UVGI solutions are addressed in this report, and data is summarized from some previous applications.

## **2. Introduction and Background**

The effects of ultraviolet light on microorganisms were discovered in the 1800s and several scientific studies on UV were published over a century ago. The first studies that attempted to quantify the effects of UV irradiation of microorganisms were published in the 1920s (Bedford 1927, Gates 1929). In these studies the disinfection rates for bacteria were determined in terms of the UV irradiance and dose. Luckiesh et al (1949) appears to have been the first to publish usable data on the irradiation of molds.

By 1950 it had been established that UV irradiation was effective at disinfecting both air and surfaces, and engineering applications were being developed. General Electric catalogs detailed many UV applications including various methods of installing UV lamps inside ducts and air conditioners (Buttolph and Haynes 1950, GE 1950). At this time it was not generally known that mold growth on cooling coils could cause respiratory problems. In 1954 it was demonstrated by Harstad et al (1954) that installation of UV lamps in air conditioners would reduce airborne contamination. It was further noted in this published study that microorganisms were impinging upon internal AHU surfaces.

It had been realized as early as 1958 that bacteria could grow on cooling coils (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 fact that microbes growing in air handling equipment could be disseminated by ventilation systems and cause respiratory infections became widely recognized in the late 1960s and early 1970s in both the medical and engineering fields (Banaszak et al 1970, Schicht 1972, Zeterberg 1973). It was widely known 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) published a book detailing many applications of UVGI, including health care applications in which the UV lamps are specifically placed upstream of the cooling coils and downstream of the filters.

By the late 1970s it was understood that UVGI could be used to control microbial growth inside air handling equipment. In 1985 Phillips published a design guide in which the first definitive description of applications of UV lamps for the control of microbial growth on cooling coils were presented (Phillips 1985). This design guide, "Germicidal Lamps and Applications" provides details of how to locate lamps at specific distances from cooling coils, and referred to

installations that were already in operation at the time. Apparently, Europeans had been using such systems prior to 1985 but no publications exist to document such applications.

In January of 1996 the first UVGI system in the U.S. designed for controlling microbial growth on cooling coils was installed by Public Service of Omaha (PSO) in Tulsa. Tom McKain of PSO reports that the idea of irradiating their fouled cooling coils came both from Dr. Richard Shaughnessy of Tulsa University (TU), and from a European professor who could not be identified (Kowalski 2003). PSO hired Steril-Aire to implement the system, which was found to be highly effective after studies by TU researchers. Steril-Aire later filed a patent, claiming they had invented the application of UVGI to microbial growth control.

Table 1 summarizes the critical events described previously insofar as they can be assigned any specific dates.

American Air & Water Technology

**Table 1: Chronology of UVGI Systems Development**

<b>Years</b>	<b>Event</b>
1870 (circa)	Bactericidal Effects of UV light discovered
1877	First demonstration of UV water disinfection (AWWA 1971)
1909	First UV applications for water disinfection
1916	First USA applications of UV for water disinfection
1920s	First studies on air and surface disinfection with UV (Bedford 1927, Gates 1929)
1936	First hospital air disinfection application (Hart 1936)
1937	First school air disinfection application (Wells 1955)
1944	Concerns first raised about microbial growth on cooling coils in hospitals (Cole 1964)
1949	Luckiesh demonstrates UV disinfection of mold on surfaces
1950	GE catalogs recommend placing UV lamps inside air conditioning units (Buttolph and Haynes 1950, GE 1950)
1954	Harstad et al (1954) demonstrate effectiveness of UV inside air conditioners
1958	Microbial growth on air conditioners linked to respiratory problems (Anderson 1959, Walter 1969)
1968	Growth of microbes on filters and dust inside air-conditioning ducts was first demonstrated by Whyte (1968).
1970s	Microbial growth on cooling coils becomes widely recognized (Banaszak et al 1970, Schicht 1972, Zeterberg 1973)
1974	Grun and Pitz detail the use of UV for internal AHU surface disinfection
1977	Luciano details installation of UV lamps in air handling units downstream of filters and upstream of cooling coils
1980s	Conditions for microbial growth inside HVAC equipment quantified (Gunderman 1980, Ager and Tickner 1983, Spendlove and Fannin 1983)
pre-1985	First cooling coil disinfection systems installed in Europe
1985	Phillips catalog details cooling coil disinfection system installation
early 1990s	Disinfection of cooling coils is widely understood and discussed by researchers
1995	Dr. Richard Shaughnessy discusses cooling coil irradiation at a seminar, attended by Public Service of Oklahoma (PSO)
January, 1996	PSO contracts Steril-Aire to install cooling coil disinfection system based on recommendations from others
February, 1996	Steril-Aire makes claims to have invented cooling coil UV disinfection

### **3. Microbial Disinfection Model**

A microbial population subject to UV exposure will tend to decay exponentially over time. The survival fraction at any time  $t$  after exposure can be defined by the following single stage exponential decay equation:

$$S = e^{-kt} \quad (1)$$

where  $k$  = UV rate constant,  $\text{cm}^2/\mu\text{J}$

Figure 1 illustrates the exponential decay curve on a logarithmic scale with various values of  $k$ . The slope of the logarithmic decay curve (the slope of the line in Figure 1) is called the rate constant. The rate constant will determine how fast the population decreases under exposure. The value of the rate constant depends on both the species and the UV irradiance.

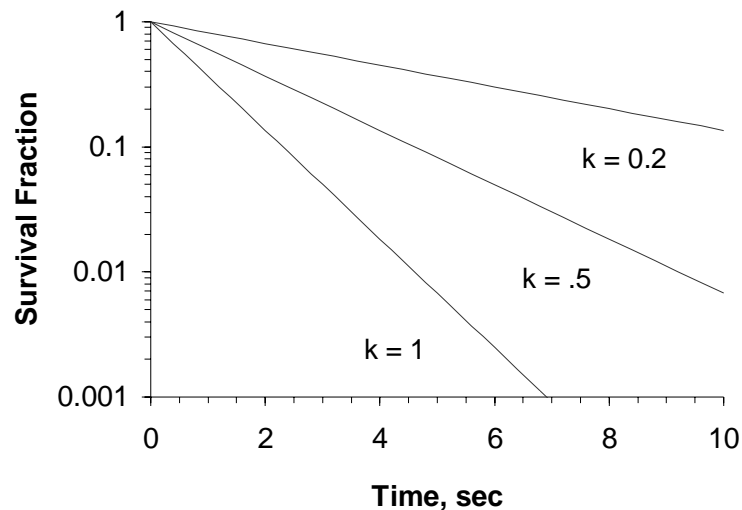


Figure 1: Survival curves for various rate constants.

The rate constant determines how fast the microbial population decays under the influence of UV. The UV irradiation may vary in intensity. The variation of irradiance is accounted for by a multiplier designated  $I$ . The classic exponential decay equation is then written as:

$$S = e^{-kIt} \quad (2)$$

In the form shown in equation (2), the rate constant  $k$  is known as the standard rate constant and it represents the susceptibility of the species for unit intensity only. In general,  $k$  is unique to each species. Often the quantity ' $It$ ' is combined into a single term called the dose. The dose can therefore be defined as:

$$D = It \quad (3)$$

When the dose is defined as in equation (3), the exponential decay equation is simply written as:

$$S = e^{-kD} \quad (4)$$

Sometimes a microbial population under UV exposure behaves as if it is two separate populations – one that succumbs rapidly and another that resists the factor. This effect has often been referred to as tailing or as nonlogarithmic survivor curves (Fujikawa and Itoh 1996, Moats et al 1971). Under these conditions the result is a two-stage decay curve. The two-stage curve is treated mathematically as if it were two distinct and separate populations that are simply added together. Each population has a unique rate constant, denoted by  $k_1$  and  $k_2$ . The fraction of the population that is resistant is denoted by  $f$ , while the complementary fraction is denoted by  $(1-f)$ , as follows:

$$S = (1 - f)e^{-k_1It} + fe^{-k_2It} \quad (5)$$

Figure 2 shows a survival curve fitted to equation (7.12) based on UVGI data for *Streptococcus pyogenes*. The curve was fitted by splitting equation (5) into two halves and fitting them individually to the split data set. The intercept of the second stage provided the population fraction.

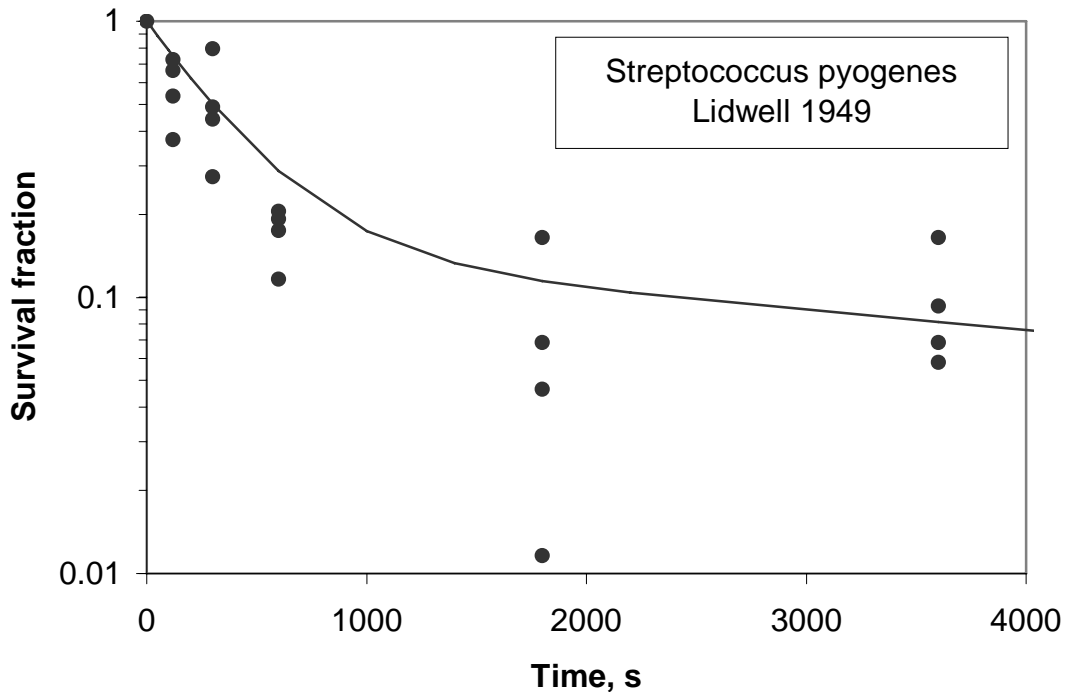


Figure 2: Survival of *Streptococcus pyogenes* under UVGI exposure. Two stage curve fitted to data from Lidwell (1949).

Data on two stage decay curves is limited and most of the available data for UVGI disinfection is for single stage curves only. A summary of microbial rate constants is provided in Appendix A.

American Air & Water, Inc.

#### **4. Cooling Coil Disinfection Model**

In typical cooling coil disinfection systems, a UV lamp, or array of UV lamps, is positioned so as to irradiate a coil surface. In the example shown in Figure 3 UV lamps are positioned so as to irradiate both the upstream and downstream sides of a cooling coil. Often, it is not possible to position lamps on both sides of a coil like this and only one side is irradiated. Lamps are often positioned in a crossflow arrangement in which the axis of the lamp runs perpendicular to the fins of the coil. The orientation of the lamp is not necessarily critical and lamps may be positioned horizontally, vertically, or at any angle relative to the coil surface. Lamp position will impact the irradiance levels at the coil surface but adjusting the total wattage, number of lamps, reflectivity, and other factors can compensate for less than optimum positioning of the lamp.

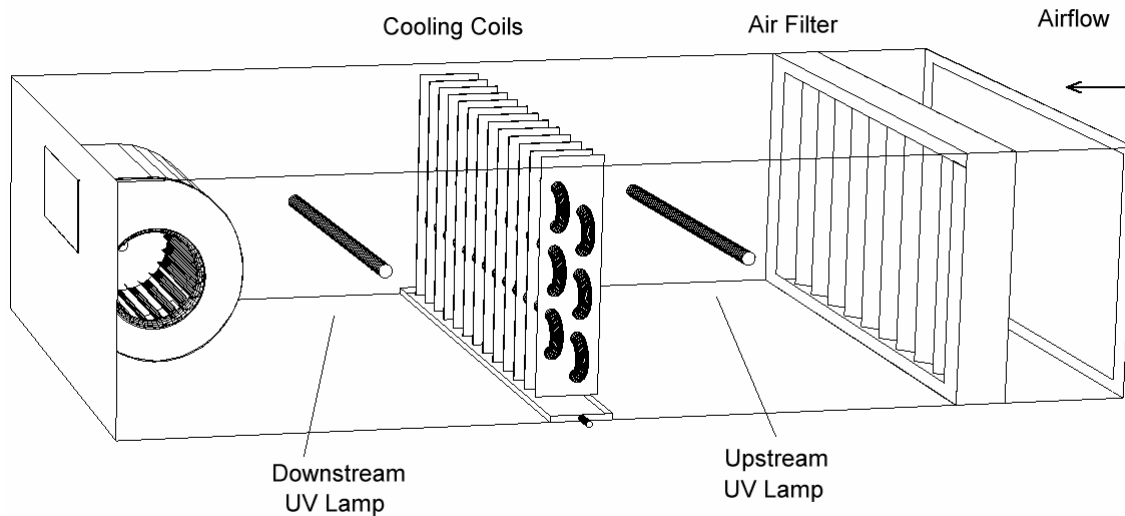


Figure 3: Air handling unit with UV lamps irradiating both upstream and downstream sides of the cooling coil.

When a single lamp is positioned with its axis parallel to the coil surface, the irradiance at any point on the coil surface can be determined using the view factor model of the lamp as a cylinder, as detailed by Kowalski et al (2000). Computer algorithms for this view factor model have been provided by Kowalski (2001 & 2003). The view factor model has been demonstrated to provide fairly accurate agreement with actual lamp irradiance measurements. Alternate lamp models have been proposed by others but there is either limited agreement with lamp data or a lack of quantitative data on the models (IESNA 2000, Krasnochub 2005). The view factor model can be used to generate irradiance profiles and contours such as those shown in Figure 4 and Figure 5, in which a single cylindrical lamp irradiates a rectangular cooling coil surface. The peak irradiance can be seen as a blunt outline of the cylindrical lamp.

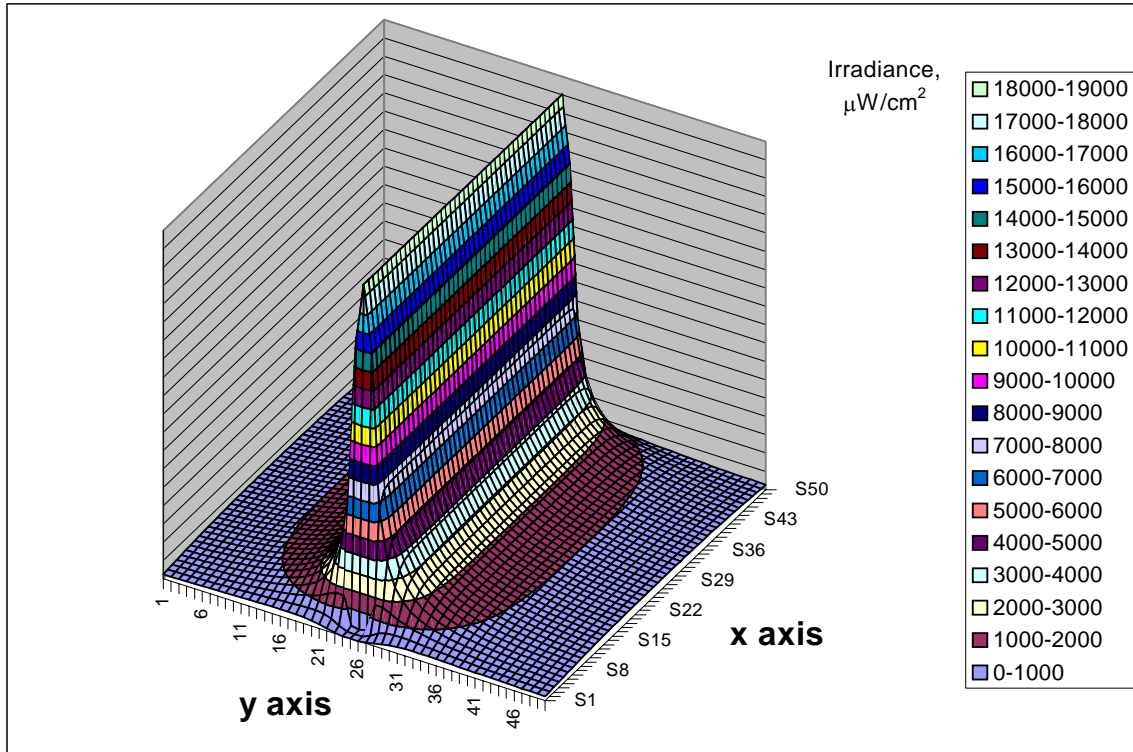


Figure 4: Example of irradiance profile on a cooling coil surface (x-y axes) from a single UV lamp located a short distance away.

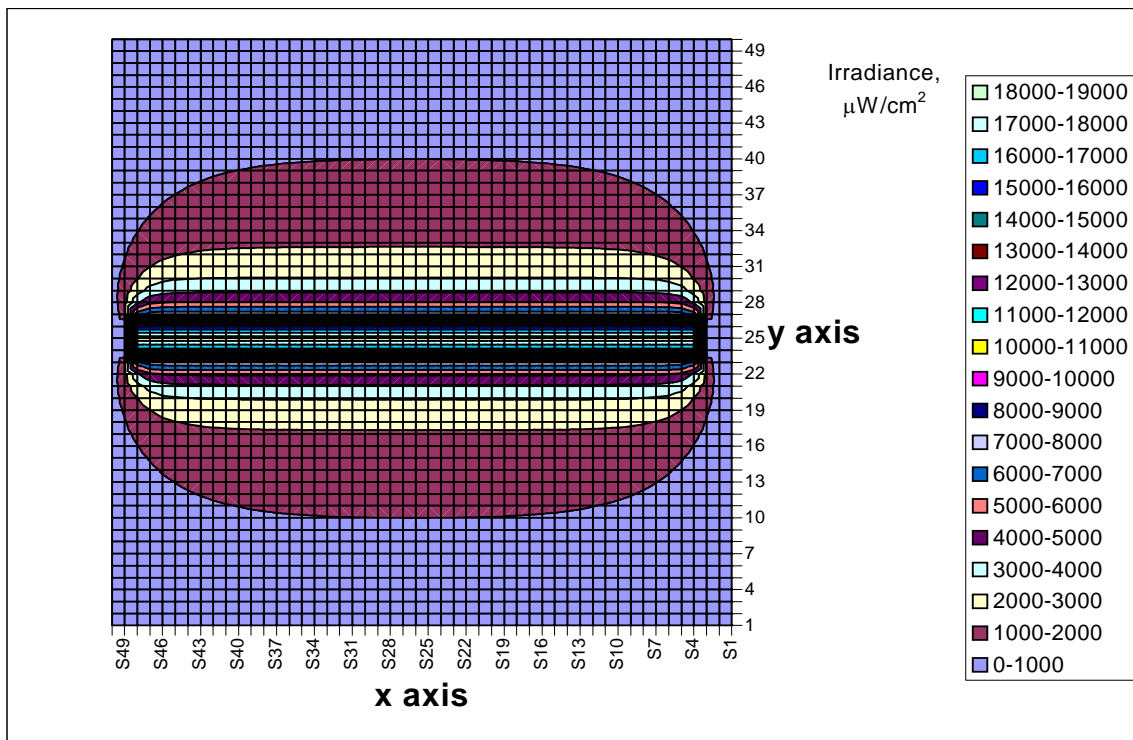


Figure 5: Irradiance contour on the cooling coil face (x-y axes) from the example in Figure 4.

Placing a UV lamp in front of a cooling coil entrance or exit plane will produce an irradiance contour on the leading edges or exit edges of the coil fins similar to that of Figure 5. Only the front surface (or back surface) irradiance levels can be predicted with certainty because determination of the irradiance within the cooling coil fins is an exceedingly complex problem that involves a limited field view factor and the reflective characteristics of the fins and coil tubes. At present, predictions of the surface irradiance must suffice as an indicator of the adequacy of UV exposure levels, but photometer measurements can also be used to confirm irradiance levels upstream and downstream. The ultimate confirmation of the adequacy of UV irradiance levels can only be obtained via surface sampling for spores. An alternative indicator of the effectiveness of UVGI may be coil performance, since the elimination of surface contamination should theoretically restore cooling coil performance to original design values.

Under UV exposure, the disinfection of cooling coil surfaces follows the basic mathematical decay models detailed in the previous section. Because the exposure times are extended in these types of surface disinfection systems, it is appropriate to use the two-stage decay equation to define the disinfection rates. The reason is that if a second stage does exist (i.e. for any mold or bacterial spore) it will likely become the only remaining stage after relatively brief initial exposure period. That is, the first stage will show rapid decay, after which only the second stage remains. Since the second stage becomes dominant in the long run, it is a better predictor than the single stage rate constant. However, few second stage rate constants are known with any certainty and predictive methods generally rely on theoretical values.

Figure 6 shows an example of a two stage decay curve of *Aspergillus niger* compared with predictions from a single stage model. The single stage model (in red) shows a log-linear decrease in microbial population over time, while the two-stage model (in blue) shows a second stage (a tail) becoming dominant after about 1000 seconds. It is clear that after extended exposure the single stage model will grossly overpredict the survival rate of the spores. This two stage behavior under prolonged exposure is typical for most microbes and indicates the need to use the two stage model when evaluating cooling coil surface disinfection. Data for the single stage is based on IESNA (2000) while the two stage curve is based on laboratory data from UVDI (2000).

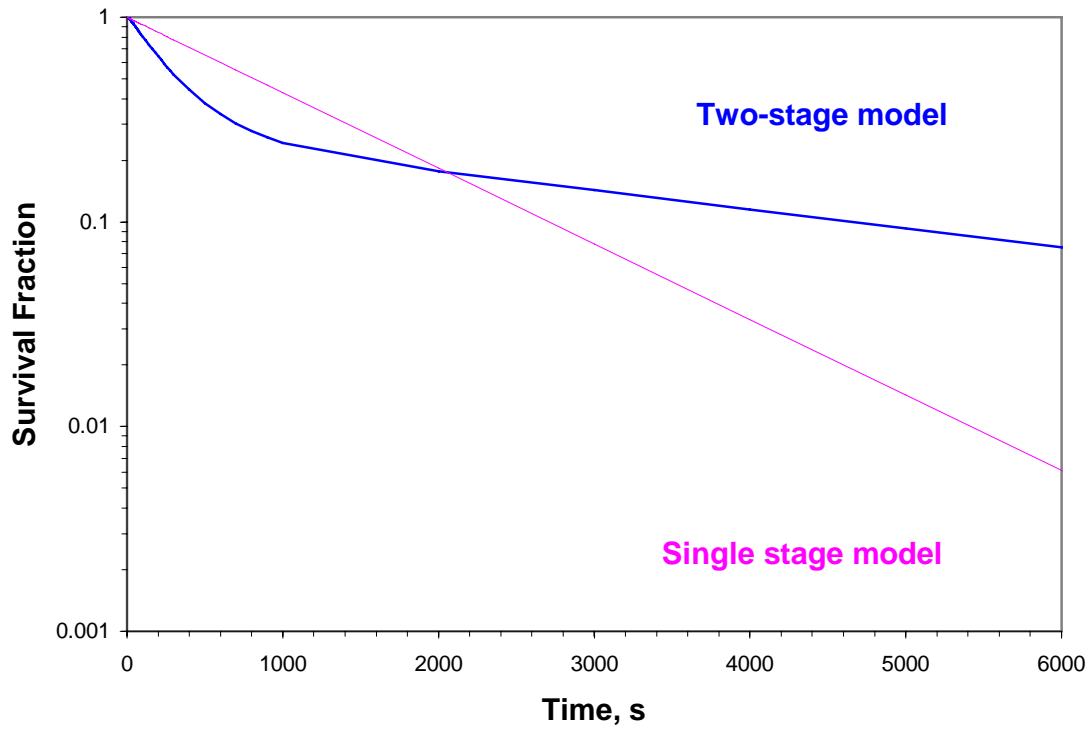


Figure 6: Comparison of a single stage model vs. a two stage model of the inactivation of *Aspergillus* spores under UV exposure of  $50 \mu\text{W}/\text{cm}^2$ . The single stage model will underestimate the required dose for sterilization.

American Air & Water, Inc.

## **5. Performance of Cooling Coil Disinfection Systems**

Although studies on the inactivation of mold spores and inhibition of mold growth by UV abound in the literature, information on the actual disinfection of cooling coils remains limited and reports of successful disinfection are primarily anecdotal, although some formal studies are underway (EPRI 2004, Shaughnessy et al 1999). There is, however, no reason to believe that the anecdotal reports are not accurate, and the indications are that disinfection of cooling coils with UV is so effective that payback periods of about 2-4 years are possible. That is, the cleaning of the coils under UV exposure proceeds so rapidly that fouled coils are restored to pristine condition and save energy and maintenance costs so effectively that the retrofit of a UV coil cleaning system pays for itself in about 2-4 years.

Theoretically, continuous exposure of cooling coil surfaces to UV should result in eradication of virtually all surface contamination within a few hours or days, depending on the irradiance levels. That is, any contamination on the exposed surface of the coils (entrance or exit respectively) should be sterilized rapidly. Figure 7 shows a system for which surface samples taken by the author indicated virtual sterilization of the leading edges after two weeks of operation.



Figure 7: A UVGI system installed in front (upstream) of a cooling coil that sterilized the front face of the coil after two weeks of operation.

Contamination on the internal surfaces of the cooling coil fins should also be sterilized over time, but it is difficult to predict how much time this might require. It does appear that, based on anecdotal field reports, that a few weeks or months is all that is required to restore coils to original design operating conditions, suggesting that internal coil contamination is sterilized in these time periods.

American Air & Water, Inc.

## **6. Economics of Cooling Coil Disinfection Systems**

The economic savings that can result from the installation of a UV cooling coil disinfection system can be estimated by comparing the operating costs after installation with the operating costs before installation, minus the cost of installing and operating the UV system. Ideally, operating data would be drawn from field test results, but this necessitates installing such a system first. Little published data is available for installed systems but anecdotal evidence suggests that UV disinfection systems are fully capable of restoring a fouled cooling coil to approximately the original design operating conditions. The cost savings will then depend on how much coil fouling has occurred and how far the system capacity has been diminished in comparison with the original design conditions. Table 1 summarizes the basic costs and the basic savings of UV cooling coil disinfection systems.

**Table 1: Costs vs. Savings of Cooling Coil Disinfection**

Costs	Savings
First Cost of installation	Fan energy savings
Operating Cost of UVGI	Cooling energy savings
Maintenance costs of UVGI	Maintenance savings

The first cost of the UVGI system will always be known, as will the operating and maintenance costs, which consist of electrical energy consumption and lamp replacement. The heat added to the system by the lamps is generally negligible and can be ignored, and furthermore, in cold climates the heat becomes a credit but this will also be ignored. The energy savings will result from two effects, the first being the reduced pressure drop through the coils once the fouling is removed, and the second being the increased rate of heat transfer from the coils when the fouling film is gone. Both of these can be significant, as can the reduction or elimination of maintenance on the cooling coils. Since the coils will be maintained in a clean condition, there is likely to be no requirement for periodic cleaning of the coils. In fact, since the UV system will maintain the coils in pristine condition, the lifetime of the coil will likely be extended well beyond the normal lifespan of unirradiated cooling coils, but this aspect of the savings will be difficult to quantify until field data is accumulated from installations.

In order to estimate cost savings, it is necessary to assume that 1) the cooling coil is fouled, which is usually true if a system is being considered, and 2) the fouling will be completely eliminated and the coils restored to design condition, which is reportedly the usual case. Alternatively, a UV system may be installed on a brand new cooling coil, in which case the savings would have to be estimated based on the projected rate of fouling.

The cost savings in dollars of a UV cooling coil disinfection system can be written as:

$$Savings = (FE_F - FE_C) + (CE_F - CE_C) + (M_F - M_C) - FC_{uv} - OC_{uv} - MC_{uv} \quad (1)$$

where  $FE_F$  = Fan Energy cost, Fouled (\$)
   
 $FE_C$  = Fan Energy cost, Clean (\$)
   
 $CE_F$  = Cooling Energy cost, Fouled (\$)
   
 $CE_C$  = Cooling Energy cost, Clean (\$)
   
 $M_F$  = Maintenance cost, Fouled (\$)
   
 $M_C$  = Maintenance cost, Clean (\$)
   
 $FC_{uv}$  = First Cost of UV (\$)
   
 $OC_{uv}$  = Operating Cost of UV (\$)
   
 $MC_{uv}$  = Maintenance Cost of UV (\$)

The fan energy in kW is computed as follows:

$$FE = \frac{dP \cdot CFM}{6350(0.75 \cdot 0.75)} \cdot 0.7355 \quad (2)$$

where  $dP$  = pressure drop, in.w.g.
   
 $CFM$  = airflow, cfm
   
0.7355 = conversion factor from BHP to kW
   
0.75 = typical motor efficiency
   
0.75 = typical fan efficiency
   
6350 = conversion factor (in.w.g-cfm) to BHP

The fan energy savings is then the fan energy in the operating condition (fouled coils) minus the fan energy under design conditions.

The cooling energy savings in kW is computed as follows:

$$CE = \left( \frac{CL}{3412 \cdot COP} \right) \quad (3)$$

where  $CL$  = the capacity loss due to fouling, Btuh
   
 $COP$  = Coefficient of Performance
   
3412 = conversion from Btuh to kW

The COP can be computed as the seasonal energy efficiency ratio (SEER) divided by 3.412. The typical value for the SEER is about 9 or 10, and the respective COP would be about 2.64 – 2.93.

The maintenance cost Before,  $M_B$ , can vary and depends on local facility procedures. Cooling coil maintenance is typically a few hours of labor a year, and may vary from a few hundred to a few thousand dollars. A reasonable estimate for small cooling coil units might be about  $M_B = \$500$  a year. Presumably, there will be no maintenance cost After, or  $M_A = 0$ .

The first cost of the UV system,  $FC_{uv}$ , will be established at the beginning of any project and no estimates can be provided. The operating cost,  $OC_{uv}$ , of the UV system is simply the electrical energy consumed by the lamp and ballast. The energy cost can be written as follows:

$$OC = \frac{W \cdot 8760}{1000} P_c \quad (4)$$

where  $W$  = total watts of power consumed by lamp fixture

$P_c$  = power charge (typically 0.08 – 0.1 \$/kWh)

8760 = hours of operation per year (continuous assumed)

1000 = conversion from kW to W

The maintenance cost of the UV system consists of the annual replacement of the UV lamps, which is simply the cost per lamp times the number of lamps. This cannot be estimated in advance and will depend on the particular project.

Application of the above equations can be demonstrated through an example of a typical cooling coil disinfection system. Consider a system with the following parameters:

- Airflow, cfm - 48,500CFM
- Cooling Coil leaving air temperature: 52 degrees F.
- Cooling Coil pressure drop, 0.75 in.w.g.
- UV wattage – 552W UVC output.
- UV lamp fixture first cost - \$3,528 per total number of fixtures per coil.
- UV lamp installation labor cost, \$1000.
- UV lamp replacement bulb cost - \$1,800 annually.
- Annual hours of cooling – approximately 4,500 hours per year.
- Cost per kWh, \$0.09.
- COP = 4.1 (typical for chilled water system)
- Cooling Load (design), 1,500,000 Btuh (assumed)

Keikavousi (2004) reports that a 27 year old system retrofitted with UV had a reduction in fan static pressure from 1.8 iwg to 0.7 iwg. The fan energy in our example above assumes only a fouled condition of 0.9 iwg, reducing to 0.75 after UV installation. The fan energy under design conditions is:

$$FE = \frac{0.75 \cdot 48,500}{6350(0.75 \cdot 0.75)} \cdot 0.7355 = 7.49 \text{ kW}$$

The fan energy under fouled conditions (assumed 0.9 in.w.g.) is:

$$FE = \frac{0.9 \cdot 48,500}{6350(0.75 \cdot 0.75)} \cdot 0.7355 = 8.988 \text{ kW}$$

The fan energy savings (Fouled-Clean) is:

$$FE_{F-C} = (8.988 - 7.49)4500 \cdot 0.09 = 607 \$$$

The cooling energy (design operating conditions) is:

$$CE = \left( \frac{1,500,000}{3412 \cdot 4.1} \right) = 107.2 \text{ kW}$$

Assuming a 20% loss due to fouling, the energy savings would be:

$$CE_{F-C} = (0.20 \cdot 107.2) \cdot 4500 \cdot 0.09 = 8685 \$$$

The operating costs are:

$$OC = \frac{552 \cdot 8760}{1000} 0.09 = 435 \$$$

The total savings can then be summed up as follows, assuming \$1000 in maintenance savings:

$$Savings = (607) + (8685) + (1000) - 3528 - 435 - 1800 = 4529 \$$$

The payback (PB) period can be approximated by dividing the initial cost by the annual savings as follows:

$$PB = \frac{3528}{4529} = 0.8 \text{ years}$$

Some examples of estimates of the savings that might be accrued from the use of cooling coil disinfection systems in health care facilities are provided in Appendix D and Appendix E. In Appendix D summaries for six facilities are provided showing inpatient and outpatient occupancies, number of clinical procedure rooms and number of procedures performed. Appendix E provides estimated costs for cooling coil disinfection systems, in-duct UV systems, and operating room UV systems, along with estimated savings based on assumptions regarding nosocomial infection rates and operating costs. Although the available data on nosocomial infection rates due to airborne infections is not specific enough to isolate the true savings that might be anticipated, the ball-park figures provided in Appendix E clearly show the potential savings are great and that payback periods computed from these estimates would be in the range of 1-2 years or less, similar to the payback periods demonstrated previously.

## **7. Guidelines for Cooling Coil Disinfection Systems**

Several guidelines have been recently introduced, or are in preparation that address the use of UV for either cooling coil disinfection or air disinfection (GSA 2003, NIOSH 2005, IUVA 2005). Based on the literature, including draft guidelines from IUVA (2005), and the analysis previously presented, certain basic design guidelines can be summarized. These are as follows:

- **Guidelines for Cooling Coil Disinfection**
- Minimum Filtration: MERV 6
- Recommended Filtration: MERV 8-11
- Maximum air velocity of between 400-500 fpm
- Maximum air temperature between 40°F-110°F
- Maximum ballast operating temperature of 40°C or 50°C (104°F or 122°F) depending on ballast
- Lamp placement: upstream, downstream, or both sides of coils
- Lamp distance from coil face: 1-4 feet (30-120 cm)
- **Exposed Coil Surface:**
  - Recommended coil average irradiance: 50-500  $\mu\text{W}/\text{cm}^2$
  - Minimum coil irradiance: 50  $\mu\text{W}/\text{cm}^2$
  - Minimum coil irradiance in any corner or side: 10  $\mu\text{W}/\text{cm}^2$
- **Opposite Coil Surface (if unexposed)**
  - Recommended coil average irradiance: 50-100  $\mu\text{W}/\text{cm}^2$
  - Minimum coil average irradiance: 10  $\mu\text{W}/\text{cm}^2$
  - Minimum coil irradiance in any corner or side: 1  $\mu\text{W}/\text{cm}^2$

The above recommendations are preliminary (per IUVA 2005) and should not be considered to be strict requirements as these matters are still under study. In addition to the above guidelines, it is recommended that UV lamp ballasts be placed externally if possible, or, if placed internally, be shielded from any heat sources. All electrical wiring should be in accordance with UL/ETL requirements. Alarms or disconnect switches should be included to disengage the UV lamps if an access door is opened. Warning signs should be placed in the vicinity and proper training given to maintenance personnel. UV lamps should be handled with care and used lamps disposed of in accordance with regulations regarding mercury content.

As verification of coil disinfection, surface sampling for fungi and/or bacteria could be performed before UV lamp installation, and then follow-up testing could be performed about 2 weeks or any time later. Major reductions in coil contaminants would suggest effective disinfection while the absence of all fungal contamination would indicate complete sterilization. As an alternative to microbiological testing, coil performance could be monitored over time to verify that the cooling coil heat transfer and pressure drop characteristics are being returned to design conditions, a process that requires an unknown amount of time, but for highly fouled coils it may require weeks or months.

## **8. Hospital Air & Surface Disinfection Systems**

UVGI systems have been in use in some operating rooms since at least 1937 (Hart and Sanger 1939). Reductions in post-operative infection rates of about 24-44% have been reported (Goldner and Allen 1973). Duke University has successfully used overhead UVGI systems to maintain a low level of orthopedic infections (Lowell et al 1980). Upper room UVGI systems have been used at The New England Deaconess Hospital, The Infant and Children's Hospital in Boston, The Cradle in Evanston, and St. Luke's Hospital in New York, to reduce surgical site infections by a net average of 68%, and for the control of respiratory infections, which decreased by a net average of 50% (Overholt and Betts 1940, Del Mundo and McKhann 1941, Sauer et al 1942, Higgons and Hyde 1947). The Home for Hebrew Infants in New York successfully brought a halt to a Varicella epidemic using UVGI (Wells 1955). Limited mention is made in most health care literature of UVGI, although some recent guidelines have acknowledged its potential effectiveness (CDC 2003, ASHRAE 2003).

A growing list of anecdotal reports, and some clinical studies, have addressed the apparent effectiveness of UVGI systems in health care facilities. These reports address the usefulness of UVGI in disinfecting cooling coils, reducing energy costs associated with cooling coils, controlling respiratory infections and complaints, sterilizing sources of TB, SARS, and other bacteria and viruses, addressing bioterrorism concerns, and controlling mold in homes. A summary of these reports, culled from engineering trade magazines, journals, Internet and paper news media, and private reports has been included in Appendix F.

The use of UVGI to clean cooling coils in hospital ventilation systems has the same economic benefits as those addressed in the previous sections of this report. However, the removal of mold and bacterial slime from cooling coils is much more important in the hospital environment which should be kept cleaner than the average commercial office building. That is, environmental bacteria and mold spores may pose hazards to patients in hospitals, especially those with impaired immune systems or burn victims. Microbial levels on surfaces and in the air need to be lower in hospitals due to the higher risks of nosocomial infection. The disinfection of cooling coils is one way to reduce microbial loading in hospitals. In theory, the requisite levels of air filtration should keep microbial contamination from accumulating on cooling coils, which are typically downstream of the filters, but casual inspections of hospital cooling coils and ductwork typically show levels of biocontamination above and beyond what would be expected with such high efficiency filters installed. The reasons for the apparent penetration of the filters are unclear but may be due to poorly fitting filters, leaking filters "bypass factor", or the performance of filter change-outs while the ventilation system continues to operate. The installation of a UVGI cooling coil disinfection system should resolve such problems and contribute to net reductions of biocontamination in hospitals. The use of dual purpose UVGI systems that both clean coils and disinfect air, should also enhance the

reductions of microbial loading.

Nosocomial infections include many diverse diseases, the sources and etiology of which are uncertain at present. Table 3 summarizes nosocomial agents that have the potential to transmit by the airborne route. The majority of nosocomial agents are potentially airborne, although most of the actual transmission is probably through direct contact (Kowalski 2005). The degree to which a cooling coil disinfection system will decrease nosocomial infections is probably quite limited, although the cost savings alone should justify such systems in any health care facility. The degree to which air and surface disinfection systems can reduce nosocomial infections is much more quantifiable, and a number of studies have been performed in this regard.

American Air Systems Inc.

**Table 3: Nosocomial Agents with Airborne Transmission Potential**

AIRBORNE PATHOGEN	TYPE	PRIMARY INFECTION CAUSED	Annual Cases	Annual Fatalities
Varicella-zoster virus	C	chickenpox	common	250
Streptococcus pyogenes	C	scarlet fever, pharyngitis	213,962	-
Streptococcus pneumoniae	C	lobar pneumonia, sinusitis, meningitis	500,000	50000
Staphylococcus aureus	E	staphylococcal pneumonia, opportunistic	2,750	-
Serratia marcescens	E	bacteremia, endocarditis, pneumonia.	479	-
SARS virus	C	Severe Acute Respiratory Syndrome	(10)	(?)
Rubella virus	C	rubella (German measles)	3,000	none
Rhizopus stolonifer	NC	zygomycosis, allergic reactions	rare	-
Respiratory Syncytial Virus	C	pneumonia, bronchiolitis	common	rare
Pseudomonas aeruginosa	NC	pneumonia	2,626	-
Pneumocystis carinii	NC	pneumocystosis	rare	rare
Parainfluenza virus	C	flu, colds, croup, pneumonia	common	-
Nocardia brasiliensis	NC	nocardiosis	uncommon	-
Nocardia asteroides	NC	nocardiosis	uncommon	rare
Mycobacterium tuberculosis	C	tuberculosis, TB	20,000	-
Mucor plumbeus	NC	mucormycosis, rhinitis	rare	rare
Moraxella	E	otitis media, opportunistic	rare	0
Measles virus	C	measles (rubeola)	500,000	rare
Legionella pneumophila	NC	Legionnaire's Disease, opportunistic	1,163	10
Klebsiella pneumoniae	E	opportunistic, pneumonia	1,488	-
Influenza A virus	C	flu, secondary pneumonia	2,000,000	20000
Histoplasma capsulatum	NC	histoplasmosis, fever, malaise	common	-
Haemophilus parainfluenzae	E	conjunctivitis, pneumonia, meningitis	common	-
Haemophilus influenzae	C	meningitis, pneumonia, endocarditis	1,162	-
Cryptococcus neoformans	NC	cryptococcosis, cryptococcal meningitis	high	rare
Corynebacterium diphtheriae	C	diphtheria, toxin produced.	10	-
Coccidioides immitis	NC	coccidioidomycosis, valley fever	uncommon	-
Chlamydia pneumoniae	C	pneumonia, bronchitis, pharyngitis	uncommon	-
Cardiobacterium	E	opportunistic infections, endocarditis	rare	-
Burkholderia pseudomallei	NC	meliodosis, opportunistic	rare	rare
Burkholderia mallei	NC	Glanders, fever, opportunistic	-	none
Bordetella pertussis	C	whooping cough	6,564	15
Blastomyces dermatitidis	NC	blastomycosis, Gilchrist's Disease	rare	-
Aspergillus	NC	aspergillosis, alveolitis, asthma	uncommon	-
Alcaligenes	E	opportunistic	rare	rare
Acinetobacter	E	opportunistic/septic, meningitis	147	-

Abbreviations: C = Communicable, NC = Noncommunicable, E=Endogenous.

SARS virus

C Severe Acute Respiratory Syndrome

There are some aspects of the savings that could be expected in health care facilities that cannot be generalized or quantified exactly, such as the reduction in worker illness (nosocomial worker illnesses are an ongoing problem in health care facilities for which rates and costs are unknown at present), and possible reductions in insurance costs once such air cleaning systems are installed. The estimated costs in these examples, including the labor costs and energy costs, are based on assumptions and should not be construed to represent the actual costs for any specific installation, which need to be independently determined. The geographic area can also impact the energy

costs through climate. One related report, that addresses air cleaning and bioterrorism, is a guideline from FEMA on the subject of insurance costs that may also be used to address reductions of naturally occurring diseases and possible savings from UVGI (FEMA 2003). UVGI may also allow for the use of lower pressure drop filters (ACEEE 2005).

American Air & Water, Inc.

## **9. Hotel Air & Surface Disinfection Systems**

Hotels are often unique in that the living quarters are typically small and do not always have direct supply air, only air conditioning or heaters under occupant control. Hotels will typically have one or more central air handling units providing air to the lobbies, hallways, restaurants, and other large areas. This supply air is intended to infiltrate into the individual hotel rooms. Sometimes the individual air conditioning units may have individual outside air dampers.

Although the central air handling units in hotels may have medium-to-low efficiency filters, the room air conditioners rarely have anything more than a simple dust filter fabric. As a result, these air conditioners tend to accumulate spores over time. With the presence of condensation, these spores may even amplify and lead to air quality problems in rooms.

Regular maintenance of room air conditioners normally involves removing the unit and cleaning with an acid or fungicide once a year. In a 200-400 unit hotel where only one or two units can be cleaned per day, this means that about half the units will have months of accumulation during the times of the year they need it most – summer and fall. As a result, hotel patrons often discover that when they turn on the air conditioner it produces a somewhat unpleasant odor.

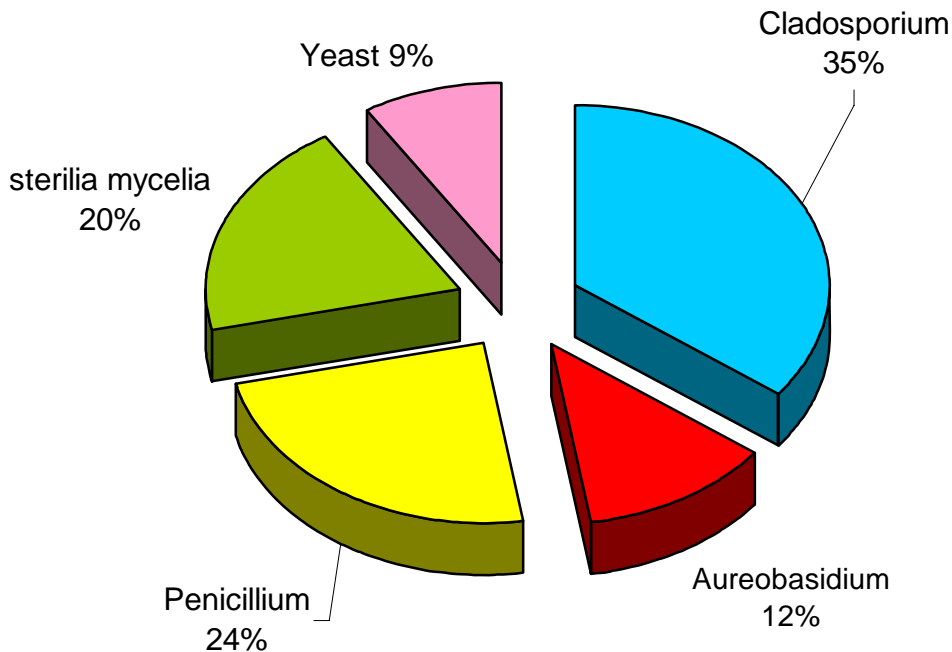


Figure 44: Fungal contamination of main air handling unit cooling coils of a large hotel. Based on author's data (Kowalski 2006).

Figure 30.6 shows the results of a survey taken by the author of the air in two hotel rooms in winter, in a hotel that had experienced water damage from a leaky roof. Although outdoor spore levels were less than 10 cfu/m<sup>3</sup>, indoor spore levels in one of the rooms exceeded a few hundred cfu/m<sup>3</sup>.

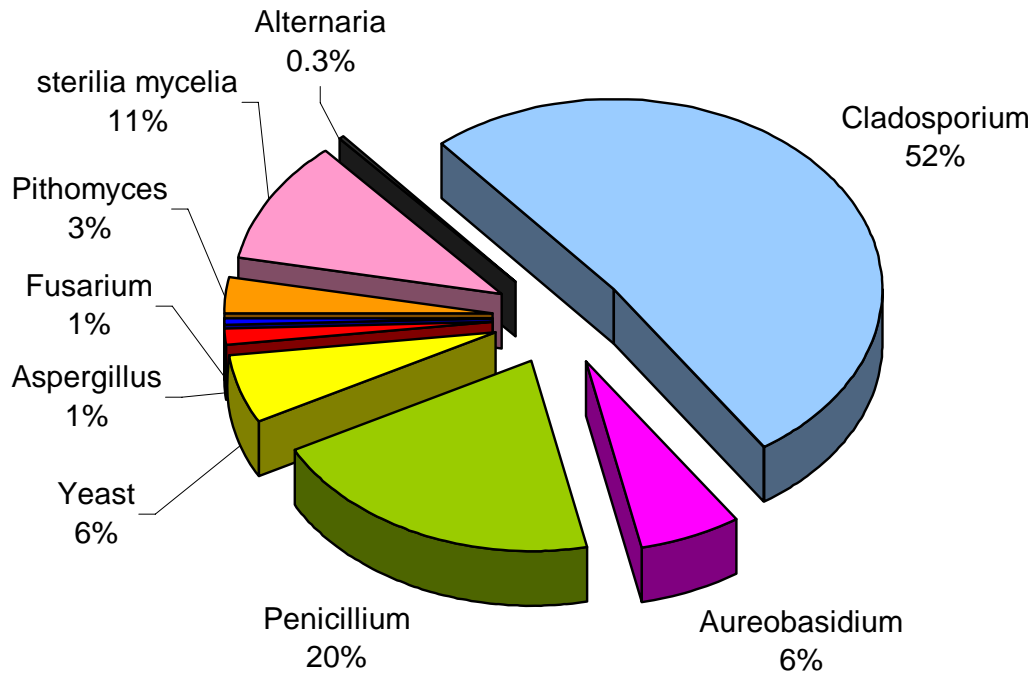


Figure 30.6: Airborne fungal spores in a hotel that had water damage. Based on average of two rooms from author's data (Kowalski 2006).

A UVGI lamp was installed in one room in the stand-alone A/C unit over the coils. Airborne fungal spores were measured before installation and after two weeks of operation. Figure SS shows the results, in which airborne levels dropped significantly. Although there was no filter, other than a dust filter, on the A/C unit, this modification appeared to greatly reduce fungal spore levels in the room. UVGI has a very limited effect on fungal spores, which tend to be resistant to UV exposure, but the constant recirculation of the room air through the unit produces a 'chronic dosing, effect – that is, if a 1% kill rate is produced by a single pass, then after several hundred passes the total kill rate will approach 99%.

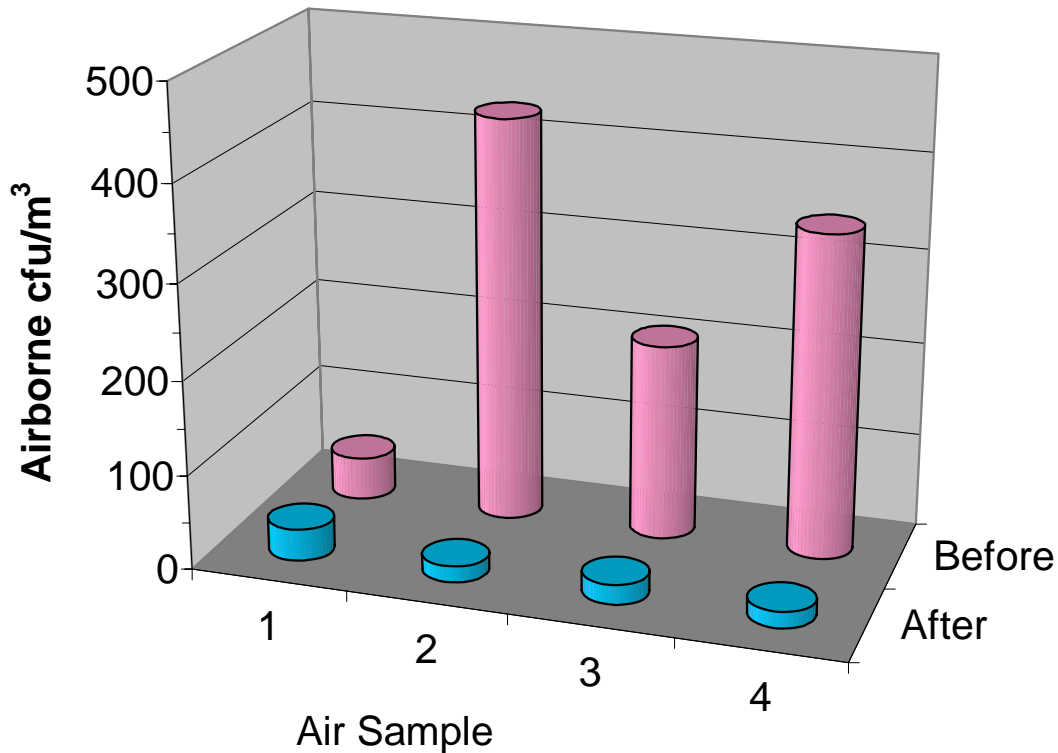


Figure: Airborne levels of fungi in a hotel room before and two weeks after UVGI installation. Based on author's data (Kowalski 2006).

One of the problems most frequently encountered in hotels is that the local room A/C units tend to accumulate mold spores on the coils and the dust filter. Condensation on the coils can then produce mold growth, which manifests itself as a foul smell when the A/C unit is turned on. These A/C units are typically subject to cleaning by maintenance personnel approximately once a year. Maintenance programs will often cycle through all the units in the hotel by removing them individually, cleaning them with steam or chemicals, and then reinstalling them. Such maintenance programs are not necessarily tied to the seasons, but may operate continuously throughout the year. What this means is that statistically up to one half of all A/C units will not have been cleaned in over six months, and if these six months are in the mold season (Spring through Fall) then up to one half the rooms may have moldy odors when the units are turned on. The odds are that many guests will experience moldy odors when they turn on the A/C units. Changes in maintenance programs may be one way to address the problem.

A more cost-effective way to control mold growth on local room A/C units, and also on central A/C units, is to install UVGI lamps around the cooling coils, provided there is sufficient space. This is relatively easy to accomplish for larger central air handling units with cooling coils, but can be problematic for local room A/C units due to the lack of space around the coils. Stand-alone A/C units

located in walls and overhead may have very limited space and UV lamps can be installed with appropriate reflectors to ensure coil exposure. Window A/C units may have no space to install UV lamps and might have to be modified to create such space, or else replaced with newer A/C units that can accommodate UV lamps.

American Air & Water, Inc.

## **10. References & Bibliography**

- Abshire RL, Dunton H. 1981. Resistance of selected strains of *Pseudomonas aeruginosa* to low-intensity ultraviolet radiation. *Appl Envir Microb* 41(6):1419-1423.
- ACGIH. 1991. Threshold Limit Values and Biological Exposure Indices for 1991-1992. Cincinnati, OH: American Conference of Governmental Industrial Hygienists.
- Aerotech. 2001. IAQ Sampling Guide. Phoenix: Aerotech Laboratories.
- Ager BP, Tickner JA. 1983. The control of microbiological hazards associated with air-conditioning and ventilation systems. *Ann Occup Hyg* 27(4):341-358.
- AIHA. 2001. Nonionizing Radiation Guide Series, Ultraviolet Radiation. Akron, OH: American Industrial Hygiene Association.
- Allegra L, Blasi F, Tarsia P, Arosio C, Fagetti L, Gazzano M. 1997. A novel device for the prevention of airborne infections. *J Clinical Microb* 35(7):1918-1919.
- Allen EG, Bovarnick MR, Snyder JC. 1954. The effect of irradiation with ultraviolet light on various properties of typhus rickettsiae. *J Bact* 67:718-723.
- Alpen EL. 1990. Radiation Biophysics. Englewood: Prentice-Hall.
- Alper T. 1979. Cellular Radiobiology. Cambridge: Cambridge University Press.
- Anellis A, Grecz N, Berkowitz D. 1965. Survival of *Clostridium botulinum* spores. *Appl/ Microbiol* 13(3):397-401.
- Antopol SC, Ellner PD. 1979. Susceptibility of *Legionella pneumophila* to ultraviolet radiation. *Appl & Environ Microb* 38(2):347-348.
- ASHRAE. 1999. ASHRAE Standard 52.2-1999. Atlanta.
- ASHRAE. 1999. Chapter 7: Health Care Facilities. In: ASHRAE, editor. ASHRAE Handbook of Applications. Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers. p 7.1-7.13.
- ASHRAE. 1999. Standard 90.1-1999: Energy Standard for Building Except Low-Rise Residential Building. Atlanta: American Society of Heating, Refrigeration and Air-Conditioning Engineers.
- ASHRAE. 2003. HVAC Design Manual for Hospitals and Clinics. Atlanta: American Society of Heating, Ventilating, and Air Conditioning Engineers.
- Asthana A, Tuveson RW. 1992. Effects of UV and phototoxins on selected fungal pathogens of citrus. *Int J Plant Sci* 153(3):442-452.
- AWWA. 1971. Water Quality and Treatment. The American Water Works Association I, editor. New York: McGraw-Hill.
- Banrud H, Moan J. 1999. The use of short wave ultraviolet radiation for disinfection in operating rooms. *Tidsskrift for den Norske Laegeforening* 119(18):2670-2673.
- Bedford THB. 1927. The nature of the action of ultra-violet light on micro-organisms. *Brit J Exp Path* 8:437-441.
- Beebe JM. 1959. Stability of disseminated aerosols of *Pastuerella tularensis* subjected to simulated solar radiations at various humidities. *Journal of*

- Bacteriology 78:18-24.
- Beggs CB, Kerr KG, Donnelly JK, Sleigh PA, Mara DD, Cairns G. 2000. An engineering approach to the control of *Mycobacterium tuberculosis* and other airborne pathogens: a UK hospital based pilot study. *Transactions of the Royal Society of Tropical Medicine and Hygiene* 94:141-146.
- Beggs CB, Sleigh PA. 2002. A quantitative method for evaluating the germicidal effects of upper room UV lights. *J Aerosol Sci* 33:1681-1699.
- Benoit TG, Wilson GR, Bull DL, Aronson AI. 1990. Plasmid-associated sensitivity of *Bacillus thuringiensis* to UV light. *Appl & Environ Microbiol* 56(8):2282-2286.
- Bishop JM, Quintrell N, Koch G. 1967. Poliovirus double-stranded RNA: Inactivation by ultraviolet light. *J Mol Biol* 24:125-128.
- Blatchley EF. 1997. Numerical modelling of UV intensity: Application to collimated-beam reactors and continuous-flow systems. *Wat Res* 31(9):2205-2218.
- Bolton JR. 2001. *Ultraviolet Applications Handbook*. Ayr, Ontario, Canada: Bolton Photosciences, Inc.
- Boss MJ, Day DW. 2001. *Air Sampling and Industrial Hygiene Engineering*. Boca Raton: Lewis Publishers.
- Bradley D, Burdett GJ, Griffiths WD, Lyons CP. 1992. Design and performance of size selective microbiological samplers. *Journal of Aerosol Science* 23(S1):s659-s662.
- Brodrotti HSv, Mahnel H. 1982. Comparative studies on susceptibility of viruses to ultraviolet rays. *Zbl Vet Med B* 29:129-136.
- Burroughs HEB. 1998. Improved filtration in residential environments. *ASHRAE J* 40(6):47-51.
- Butler RC, Lund, V., and Carlson, D. A. 1987. Susceptibility of *Campylobacter jejuni* and *Yersinia enterocolitica* to UV radiation. *Zbl Vet Med B* 29:129-136.
- Carlson HJ. 1975. Germicidal lamp inactivation of poliovirus. *Am J Publ Health* 32:1256-1262.
- Casarett AP. 1968. *Radiation Biology*. Englewood: Prentice-Hall.
- CDC. 1994. Guidelines for preventing the transmission of *Mycobacterium tuberculosis* in health-care facilities. In: CDC, editor. *Federal Register*. Washington: US Govt. Printing Office.
- CDC. 2003. Guidelines for Environmental Infection Control in Health-Care Facilities. *MMWR* 52(RR-10).
- Chang JCH, Ossoff SF, Lobe DC, Dorfman MH, Dumais CM, Qualls RG, Johnson JD. 1985. UV inactivation of pathogenic and indicator microorganisms. *Appl & Environ Microbiol* 49(6):1361-1365.
- Chick EW, A.B. Hudnell J, Sharp DG. 1963. Ultraviolet sensitivity of fungi associated with mycotic keratitis and other mycoses. *Sabouviad* 2(4):195-200.
- CIE. 2003. *Ultraviolet Air Disinfection*. Vienna, Austria: International Commission on Illumination. Report nr CIE 155:2003.
- Coggle JE. 1971. *Biological effects of radiation*. London: Wykeham Publ.
- Collier LH, McClean D, Vallet L. 1955. The antigenicity of ultra-violet irradiated

- vaccinia virus. J Hyg 53(4):513-534.
- Collins FM. 1971. Relative susceptibility of acid-fast and non-acid fast bacteria to ultraviolet light. Appl Microbiol 21:411-413.
- Corporation C. 1999. Selection Guide: Ultraviolet Germicidal Lamp.
- Darken MA, Swift ME. 1962. Effects of ultraviolet-absorbing compounds on spore germination and cultural variation in microorganisms. Applied Microbiology 11:154-156.
- David HL, Jones WD, Newman CM. 1971. Ultraviolet light inactivation and photoreactivation in the mycobacteria. Infect and Immun 4:318-319.
- David HL. 1973. Response of mycobacteria to ultraviolet radiation. Am Rev Resp Dis 108:1175-1184.
- DeGiorgi CF, Fernandez RO, Pizarro RA. 1996. Ultraviolet-B lethal damage on *Pseudomonas aeruginosa*. Current Microb 33:141-146.
- Dietz P, Bohm R, Strauch D. 1980. Investigations on disinfection and sterilization of surfaces by ultraviolet radiation. Zbl Bakt Mikrobiol Hyg 171(2-3):158-167.
- Dring GJ, Ellar DJ, Gould GW. 1985. Fundamental and Applied Aspects of Bacterial Spores. London: Academic Press.
- Drobnik J, Krekulova A. 1969. UV sensitivity of germinating culture of *B. cereus*. Folia Microbiol (Praha) 14:104-111.
- Dumyahn T, First M. 1999. Characterization of ultraviolet upper room air disinfection devices. Am Ind Hyg Assoc J 60(2):219-227.
- Eisenstark A. 1989. Bacterial genes involved in response to near-ultraviolet radiation. Advances in Genetics 26:99-147.
- El-Adhami W, Daly S, Stewart PR. 1994. Biochemical studies on the lethal effects of solar and artificial ultraviolet radiation on *Staphylococcus aureus*. Arch Microbiol 161:82-87.
- Elasri MO, Miller RV. 1999. Response of a biofilm bacterial community to UV Radiation. Appl & Environ Microbiol 65(5):2025-2031.
- Ensor DS, Hanley JT, Sparks LE. 1991. Particle-size-dependent efficiency of air cleaners. . IAQ '91. Washington: Healthy Buildings/IAQ '91.
- Erhardt L, C.P.Steinmetz. 1977. Radiation, Light, and Illumination. tx, editor. Camarillo: Camarillo Reproduction Center.
- FEMA. 2003. Reference Manual to Mitigate Potential Terrorist Attacks Against Buildings. : Federal Emergency Management Agency. Report nr FEMA 426.
- FEMA. 2003. Primer for Design of Commercial Buildings to Mitigate Terrorist Attacks. : Federal Emergency Management Agency. Report nr FEMA 427.
- FEMA. 2003. Primer to Design Safe School Projects in Case of Terrorist Attacks. : Federal Emergency Management Agency. Report nr FEMA 428.
- FEMA. 2003. Insurance, Finance, and Regulation Primer for Terrorism Risk Management in Buildings. : Federal Emergency Management Agency. Report nr FEMA 429.
- Fernandez RO. 1996. Lethal effect induced in *Pseudomonas aeruginosa* exposed to ultraviolet-A radiation. Photochem & Photobiol 64(2):334-339.
- Field AA. 1973. Operating theater air conditioning. HPAC October:91-93.

- First MW, Nardell EA, Chaisson W, Riley R. 1999. Guidelines for the application of upper-room ultraviolet germicidal irradiation for preventing transmission of airborne contagion. *ASHRAE J* 105.
- Foarde KK, Myers EA, Hanley JT, Ensor DS, Roessler PF. 1999. Methodology to perform clean air delivery rate type determinations with microbiological aerosols. *Aerosol Sci & Technol* 30:235-245.
- Foarde KK, Hanley JT, Ensor DS, Roessler P. 1999. Development of a method for measuring single-pass bioaerosol removal efficiencies of a room air cleaner. *Aerosol Sci & Technol* 30:223-234.
- Foarde KK, Hanley JT, Veeck AC. 2000. Efficacy of antimicrobial filter treatments. *ASHRAE J Dec*:52-58.
- Fuerst CR. 1960. Inactivation of bacterial viruses by physical means. *Annals of the New York Academy of Sciences* 82:684-691.
- Fujikawa H, Itoh T. 1996. Tailing of thermal inactivation curve of *Aspergillus niger* spores. *Appl Microb* 62(10):3745-3749.
- Furuhashi M, Nakamura H, Ueda I, Kozuka M. 1987? Ultraviolet irradiation of air sterilization under dynamic airflow. *unk*:2.7-2.10.
- Futter BV, Richardson G. 1967. Inactivation of bacterial spores by visible radiation. *J Appl Bact* 30(2):347-353.
- Galasso GJ, Sharp DG. 1965. Effect of particle aggregation on the survival of irradiated Vaccinia virus. *J Bact* 90(4):1138-1142.
- Gates FL. 1929. A study of the bactericidal action of ultraviolet light. *J Gen Physiol* 13:231-260.
- Germaine GR, Murrell WG. 1973. Effect of dipicolinic acid on the ultraviolet radiation resistance of *Bacillus cereus* spores. *Photochem & Photobiol* 17:145-154.
- Gillis HL. 1974. Photoreactivation and ultraviolet inactivation of Mycobacteria in air, MS Thesis. Atlanta.: Georgia Technical University.
- Gilpin RW. 1984. Laboratory and Field Applications of UV Light Disinfection on Six Species of Legionella and Other Bacteria in Water. In: Thornsberry C, editor. *Legionella: Proceedings of the 2nd International Symposium*. Washington: American Society for Microbiology.
- Glassner AS, editor. 1989. *An Introduction to Ray Tracing*. London: Academic Press.
- Glaze WH, Payton GR, Huang FY, Bureson JL, Jones PC. 1980. Oxidation of water supply refractory species by ozone with ultraviolet radiation. : U.S. EPA. Report nr 600.
- Goldstein MA, Tauraso NM. 1970. Effect of formalin, B-propiolactone, merthiolate, and ultraviolet light upon Influenza virus infectivity, chicken cell agglutination, hemagglutination, and antigenicity. *Appl Microb* 19(2):290-294.
- Griffiths WD, S.L.Upton and D.Mark. 1993. An investigation into the collection efficiency & bioefficiencies of a number of aerosol samplers. *Journal of Aerosol Science* 24(S1):s541-s542.
- Grun L, Pitz N. 1974. U.V. radiators in humidifying units and air channels of air conditioning systems in hospitals. *Zbl Bakt Hyg B*159:50-60.

- GSA. 2003. The Facilities Standards for the Public Buildings Service. Washington: Public Buildings Service of the General Services Administration.
- Gurol MD, Vatista R. 1987. Oxidation of phenolic compounds by ozone and ozone + UV radiation. *Water Res* 21:895.
- Hanley JT, D.D.Smith and D.S.Ensor. 1995. A fractional aerosol filtration efficiency test method for ventilation air cleaners. *ASHRAE Transactions* 101(1):97.
- Harm W. 1968. Effects of dose fractionation on ultraviolet survival of *Escherichia coli*. *Photochem & Photobiol* 7:73-86.
- Harm W. 1980. Biological effects of ultraviolet radiation. New York: Cambridge University Press.
- Harstad JB, H.M.Decker, A.G.Wedum. 1954. Use of ultraviolet irradiation in a room air conditioner for removal of bacteria. *American Industrial Hygiene Association Journal* 2:148-151.
- Hernandez M, Miller SL, Landfear DW, Macher JM. 1999. *Aerosol Sci & Technol* 30:145-160.
- Hill WF, Hamblet FE, Benton WH, Akin EW. 1970. Ultraviolet devitalization of eight selected enteric viruses in estuarine water. *Appl Microb* 19(5):805-812.
- Holah JT, Rogers SJ, Holder J, Hall KE, Taylor J, Brown KL. 1995. The evaluation of air disinfection systems. Gloucestershire: Campden & Chorleywood Food Research Association. Report nr R&D Report No. 13.
- Hollaender A. 1943. Effect of long ultraviolet and short visible radiation (3500 to 4900) on *Escherichia coli*. *J Bact* 46:531-541.
- Horneck G, Bucker H, Reitz G. 1985. *Bacillus subtilis* spores on Spacelab I: Response to solar UV radiation in free space. In: Dring GJ, Ellar DJ, Gould GW, editors. *Fundamental and Applied Aspects of Bacterial Spores*. London: Academic Press. p 241-249.
- Huber TW, Reddick RA, Kubica GP. 1970. Germicidal effect of ultraviolet irradiation on paper contaminated with mycobacteria. *Appl Microbiol* 19:383-384.
- IES. 1981. *Lighting Handbook Application Volume: Illumination Engineering Society*.
- IESNA. 2000. *Lighting Handbook 9th Edition IESNA HB-9-2000: Illumination Engineering Society of North America*.
- IRPA. 1985. International Radiation Protection Association Guidelines on Limits of Exposure to Ultraviolet Radiation of Wavelengths Between 180 nm and 400 nm (Incoherent Optical Radiation). *Health Physics* 49:331-340.
- Ishida H, Nahara Y, Tamamoto M, Hamada T. 1991. The fungicidal effect of ultraviolet light on impression materials. *J Prosthet Dent* 65(4):532-535.
- IUVA. 2005. *Guideline for the Design and Installation of UVGI Cooling Coil Surface Disinfection Systems*. Ayr, Ontario, Canada: International Ultraviolet Association. Report number IUVA-G04A-2005.
- IUVA. 2005. *General Guideline for UVGI Air and Surface Disinfection Systems*. Ayr, Ontario, Canada: International Ultraviolet Association. Report number

- IUVA-G01A-2005.
- IUVA. 2005. Guideline for Design and Installation of UVGI Air Disinfection Systems in New Building Construction. Ayr, Ontario, Canada: International Ultraviolet Association. Report number IUVA-G02A-2005.
- IUVA. 2005. Guideline for Design and Installation of UVGI In-Duct Air Disinfection Systems. Ayr, Ontario, Canada: International Ultraviolet Association. Report number IUVA-G03A-2005.
- IUVA. 2005. Guideline for the Testing and Commissioning of UVGI In-Duct Air Treatment Systems. Ayr, Ontario, Canada: International Ultraviolet Association. Report number IUVA-S01A-2005.
- IUVA. 2005. Draft Standard for Laboratory Testing of UVGI Air and Surface Rate Constants. Ayr, Ontario, Canada: International Ultraviolet Association. Report number IUVA-S06A-2005.
- Jagger J. 1967. Ultraviolet Photobiology. Englewood Cliffs: Prentice-Hall, Inc.
- Jensen MM. 1964. Inactivation of airborne viruses by ultraviolet irradiation. *Applied Microbiology* 12(5):418-420.
- Jensen M. 1967. Bacteriophage aerosol challenge of installed air contamination control systems. *Appl Microbiol* 15(6):1447-1449.
- Jensen PA, Schafer MP. 1998. Chapter J: Sampling and Characterization of Bioaerosols. In: Cassinelli ME, O'Connor PF, editors. NIOSH Manual of Analytical Methods, NIOSH Publication 94-113. Atlanta: National Institute for Occupational Safety and Health. p 82-112.
- Kamat AS, Pradhan DS. 1991. Influence of cellular differentiation on ultraviolet induced DNA damage and its repair mechanisms in *B. cereus*. *Indian J of Biochemistry and Biophysics* 28:83-92.
- Keller LC, Thompson TL, Macy RB. 1982. UV light-induced survival response in a highly radiation-resistant isolate of the *Moraxella-Acinetobacter* group. *Appl & Environ Microb* 43(2):424-429.
- Kelner A. 1949. Effect of visible light on the recovery of *Streptomyces griseus* conidia from ultraviolet irradiation injury. *Proc Nat Acad Sci* 35(2):73-79.
- Kethley TW. 1973. Feasibility Study of Germicidal UV Lamps for Air Disinfection in Simulated Patient Care Rooms. San Francisco, CA: American Public Health Association.
- Knudson GB. 1985. Photoreactivation of UV-irradiated *Legionella pneumophila* and other *Legionella* species. *Appl & Environ Microbiol* 49(4):975-980.
- Knudson GB. 1986. Photoreactivation of ultraviolet-irradiated, plasmid-bearing, and plasmid-free strains of *Bacillus anthracis*. *Appl & Environ Microbiol* 52(3):444-449.
- Ko G, First MW, Burge HA. 2000. Influence of relative humidity on particle size and UV sensitivity of *Serratia marcescens* and *Mycobacterium bovis* BCG aerosols. *Tuber Lung Dis* 80:217-228.
- Koller LR. 1952. Ultraviolet Radiation. New York: John Wiley & Sons.
- Kowalski WJ. 1997. Technologies for controlling respiratory disease transmission in indoor environments: Theoretical performance and economics. [M.S.]: The Pennsylvania State University.
- Kowalski WJ, Bahnfleth WP, Whittam TS. 1998. Bactericidal effects of high

- airborne ozone concentrations on *Escherichia coli* and *Staphylococcus aureus*. *Ozone Science & Engineering* 20(3):205-221.
- Kowalski W, Bahnfleth WP. 1998. Airborne respiratory diseases and technologies for control of microbes. *HPAC* 70(6):34-48.
- Kowalski WJ, W. P. Bahnfleth, T. S. Whittam. 1999. Filtration of Airborne Microorganisms: Modeling and prediction. *ASHRAE Transactions* 105(2):4-17.
- Kowalski WJ. 2000. Shedding Light on Moldy Ductwork. *Home Energy* 17(3):6.
- Kowalski WJ, Bahnfleth WP. 2000. Effective UVGI system design through improved modeling. *ASHRAE Transactions* 106(2):4-15.
- Kowalski WJ, Bahnfleth WP, Witham DL, Severin BF, Whittam TS. 2000. Mathematical modeling of UVGI for air disinfection. *Quantitative Microbiology* 2(3):249-270.
- Kowalski WJ, Bahnfleth WP. 2000. UVGI Design Basics for Air and Surface Disinfection. *HPAC* 72(1):100-110.
- Kowalski WJ. 2001. Design and optimization of UVGI air disinfection systems [PhD]. State College: The Pennsylvania State University.
- Kowalski WJ, Dunn CE. 2002. Current Trends in UVGI Air and Surface Disinfection. *INvironment Professional* 8(6):4-6.
- Kowalski WJ. 2003. *Immune Building Systems Technology*. New York: McGraw-Hill.
- Kowalski WJ. 2006. *Aerobiological Engineering Handbook: A Guide to Airborne Disease Control Technologies*. New York: McGraw-Hill.
- Kuluncsics Z, Perdiz D, Brulay E, Muel B, Sage E. 1999. Wavelength dependence of ultraviolet-induced DNA damage distribution: Involvement of direct or indirect mechanisms and possible artefacts. *J Photochem & Photobiol* 49(1):71-80.
- Kumar R. 1981. Effect of glass filtered solar radiation & of 2,4 dinitrophenol on growth of bacillus cereus & on its survival after far-UV irradiation. *Indian J of Experimental Biology* 19(April):345-348.
- Kundsin RB. 1966. Characterization of Mycoplasma aerosols as to viability, particle size, and lethality of ultraviolet radiation. *J Bacteriol* 91(3):942-944.
- Kundsin RB. 1968. Aerosols of Mycoplasmas, L forms, and bacteria: Comparison of particle size, viability, and lethality of ultraviolet radiation. *Applied Microbiology* 16(1):143-146.
- Kundsin RB. 1988. *Architectural design and indoor microbial pollution*: Oxford Press.
- Lai KM, Burge, H., and First, M. W. 2004. Size and UV germicidal irradiation susceptibility of *Serratia marcescens* when aerosolized from different suspending media. *Appl Environ Microbiol* 70(4):2021-2027.
- Levetin E, Shaughnessy R, Rogers CA, Scheir R. 2001. Effectiveness of germicidal UV radiation for reducing fungal contamination within air-handling units. *Applied & Environ Microbiol* 67(8):3712-3715.
- Lidwell OM, Lowbury EJ. 1950. The survival of bacteria in dust. *Annual Review of Microbiology* 14:38-43.

- Lin W-H, Li CS. 1999. Evaluation of impingement and filtration methods for yeast bioaerosol sampling. *Aerosol Sci & Technol* 30:119-126.
- Lindsey JL. 1997. *Applied Illumination Engineering*. Lilburn: The Fairmont Press, Inc.
- Linscomb M. 1994. AIDS clinic HVAC system limits spread of TB. *HPAC* February.
- Litonski B. 1974. Air conditioning as decontamination unit for the air of operating theatres. *Zbl Bakt Hyg B* 159:244-271.
- Little JS, Kishimoto RA, Canonico PG. 1980. In vitro studies of interaction of rickettsia and macrophages: Effect of ultraviolet light on *Coxiella burnetti* inactivation and macrophage enzymes. *Infect Immun* 27(3):837-841.
- Lojo MM. 1995. Thymine auxotrophy is associated with increased UV sensitivity in *Escherichia coli* and *Bacillus subtilis*. *Mutation Research* 347:25-30.
- Love TJ. 1968. *Radiative Heat Transfer*. Columbus: Charles A. Merrill.
- Luciano JR. 1977. *Air Contamination Control in Hospitals*. New York: Plenum Press.
- Luckiesh M, Holladay LL. 1942. Designing installations of germicidal lamps for occupied rooms. *General Electric Review* 45(6):343-349.
- Luckiesh M, Holladay LL. 1942. Tests and data on disinfection of air with germicidal lamps. *General Electric Review* 45(4):223-231.
- Luckiesh M. 1945. Disinfection with germicidal lamps: Control -- I. *Electrical World* Sep.29:72-73.
- Luckiesh M. 1945. Disinfection with germicidal lamps: Air -- II. *Electrical World* Oct.13:109-111.
- Luckiesh M. 1945. Disinfection with germicidal lamps: Water -- III. *Electrical World* Oct.27:90-91.
- Luckiesh M. 1946. *Applications of Germicidal, Erythematous and Infrared Energy*. New York: D. Van Nostrand Co.
- Luckiesh M, Taylor AH, Knowles T. 1947. Killing air-borne microorganisms with germicidal energy. *Journal of the Franklin Institute* Oct.:267-290.
- Lytle CD. 1971. Host-cell reactivation in mammalian cells. 1. Survival of ultraviolet-irradiated herpes virus in different cell-lines. *Int J Radiat Biol Relat Stud Phys Chem Med* 19(4):329-337.
- Macher JM, Alevantis LE, Chang YL, Liu KS. 1992. Effect of ultraviolet germicidal lamps on airborne microorganisms in an outpatient waiting room. *Appl Occup Environ Hyg* 7(8):505-513.
- Mason JM, Setlow P. 1986. Essential role of small, acid-soluble spore proteins in resistance of *Bacillus subtilis* spores to UV light. *J of Bact* 167(1):174-178.
- Memarzadeh F, Jiang J. 2000. Methodology for minimizing risk from airborne organisms in hospital isolation rooms. *ASHRAE Transactions* 106(2).
- Miller SL, Macher JM. 2000. Evaluation of a methodology for quantifying the effect of room air ultraviolet germicidal irradiation on airborne bacteria. *Aerosol Sci & Tech* 33:274-295.
- Mitscherlich E, Marth EH. 1984. *Microbial Survival in the Environment*. Berlin: Springer-Verlag.

- Modest MF. 1993. Radiative Heat Transfer. New York: McGraw-Hill.
- Mongold J. 1992. DNA repair and the evolution of transformation in *Haemophilus influenzae*. Genetics 132:893-898.
- Montz WE. 2000. Contamination control in hospitals. Engineered Systems 17(6):68-72.
- Morrissey RF, Phillips GB. 1993. Sterilization Technology. New York: Van Nostrand Reinhold.
- Munakata N, Rupert CS. 1972. Genetically controlled removal of "spore photoproduct" from deoxyribonucleic acid of ultraviolet-irradiated *Bacillus subtilis* spores. J Bact 111(1):192-198.
- Munakata N, Rupert CS. 1975. Effects of DNA-polymerase-defective and recombination-deficient mutations on the ultraviolet sensitivity of *Bacillus subtilis* spores. Mutation Res 27:157-169.
- Munakata N, Saito M, Hieda K. 1991. Inactivation action spectra of *Bacillus subtilis* spores in extended ultraviolet wavelengths (50-300 nm) obtained with synchrotron radiation. Photochem & Photobiol 54(5):761-768.
- Murdoch JB. 1985. Illumination Engineering. New York: Macmillan.
- Nakamura H. 1987. Sterilization efficacy of ultraviolet irradiation on microbial aerosols under dynamic airflow by experimental air conditioning systems. Bull Tokyo Med Dent Univ 34(2):25-40.
- Nardell EA. 1988. Chapter 12: Ultraviolet air disinfection to control tuberculosis. In: Kundsinn RB, editor. Architectural Design and Indoor Microbial Pollution. New York: Oxford University Press. p 296-308.
- Nardell EA, Keegan J, Cheney SA, Etkind SC. 1991. Airborne infection: Theoretical limits of protection achievable by building ventilation. Am Rev Resp Dis 144:302-306.
- NEHC. 1992. Ultraviolet Radiation Guide. Norfolk, VA: Navy Environmental Health Center, Bureau of Medicine and Surgery. Report nr Technical Manual NEHC-TM92-5.
- Nicas M, Miller SL. 1999. A multi-zone model evaluation of the efficacy of upper-room air ultraviolet germicidal irradiation. Appl & Environ Occup Hyg J 14:317-328.
- Ninomura P, Bartley J. 2001. New ventilation guidelines for health-care facilities. ASHRAE J 43(6):2933.
- NIOSH. 1972. Occupational Exposure to Ultraviolet Radiation. Cincinnati, OH: National Institute for Occupational Safety and Health. Report nr HSM 73-110009.
- NIOSH. 2002. Guidance for Protecting Building Environments from Airborne Chemical, Biological, or Radiological Attacks. Cincinnati, OH: Dept. of Health and Human Services, CDC, National Institute for Occupational Safety and Health. Report nr DHHS (NIOSH) Pub. No. 2002-139.
- NIOSH. 2003. Guidance for Filtration and Air-cleaning Systems to Protect Building Environments. Cincinnati, OH: Dept. of Health and Human Services, CDC, National Institute for Occupational Safety and Health. Report nr DHHS (NIOSH) Pub. No. 2003-136.
- Pannkoke T. 1973. Modern clean room concepts. HPAC October:63-70.

- Peccia J, Werth HM, Miller S, Hernandez M. 2001. Effects of relative humidity on the ultraviolet induced inactivation of airborne bacteria. *Aerosol Sci & Technol* 35:728-740.
- Peccia J, Hernandez M. 2001. Photoreactivation in Airborne *Mycobacterium parafortuitum*. *Appl and Environ Microbiol* 67:2001.
- Peccia J, and Hernandez, M. 2002. UV-induced inactivation rates for airborne *Mycobacterium bovis* BCG. *J Occup Environ Hyg* 1(7):430-435.
- Philips. 1985. UVGI Catalog and Design Guide. Netherlands: Catalog No. U.D.C. 628.9.
- Phillips GB, Novak FE. 1955. Applications of germicidal ultraviolet in infectious disease laboratories. *Appl Microb* 4:95-96.
- Photobiol. P. 1982. Differential sensitivity to inactivation of NUR and NUR+ strains of *Escherichia coli* at six selected wavelengths in the UVA, UVB and UVC ranges. *Photochem Photobiol* 36:525-530.
- Pizzarello DJ, Witcofski RL. 1982. *Medical Radiation Biology*. Philadelphia: Lea & Febiger.
- Poduska RA, Hershey D. 1972. Model for virus inactivation by chlorination. *J Wat Pollut Control Fed* 44(5):738-745.
- Pollard EC. 1960. Theory of the physical means of the inactivation of viruses. *Annals of the New York Academy of Sciences* 82:654-660.
- Potapchenko NG, Ilyashenko VV, Savlak OS. 1995. Inactivation of drinking water microorganisms by UV-radiation. *Mikrobiologichnyi Zhurnal* 57(1):85-91.
- Prengle HWJ. 1983. Experimental rate constants and reactor conditions for the destruction of micropollutants and trihalomethane precursors by ozone with ultraviolet radiation. *Environ Sci Technol* 17:743.
- Proctor WR, Cook, J. S., and Tennant, R. W. 1972. Ultraviolet photobiology of Kilham rat virus and the absolute ultraviolet photosensitivities of other animal viruses: Influence of DNA strandedness, molecular weight, and host-cell repair. *Virology* 49(2):368-378.
- Qualls RG, Johnson JD. 1983. Bioassay and dose measurement in UV disinfection. *Appl Microb* 45(3):872-877.
- Qualls RG, Johnson JD. 1985. Modeling and efficiency of ultraviolet disinfection systems. *Water Res* 19(8):1039-1046.
- Rahn RO, Xu P, Miller SL. 1999. Dosimetry of room-air germicidal (254 nm) radiation using spherical actinometry. *Photochem and Photobiol* 70(3):314-318.
- Rainbow AJ, Mak S. 1973. DNA damage and biological function of human adenovirus after U.V. irradiation. *Int J Radiat Biol* 24(1):59-72.
- Ramsay IA, Niedziela J-C, Ogden ID. 2000. The synergistic effect of excimer and low-pressure mercury lamps on the disinfection of flowing water. *J of Food Protection* 63(11):1529-1533.
- Rauth AM. 1965. The physical state of viral nucleic acid and the sensitivity of viruses to ultraviolet light. *Biophysical Journal* 5:257-273.
- Rea MS. 1990. *Lighting Handbook Reference & Application*, 8th Edition. New

- York: Illuminating Engineering Society of North America.
- Rentschler HC, Nagy R. 1940. Advantages of bactericidal ultraviolet radiation in air conditioning systems. HPAC 12:127-130.
- Rentschler HC, Nagy R, Mouromseff G. 1941. Bactericidal effect of ultraviolet radiation. J Bacteriol 42:745-774.
- Rentschler HC, Nagy R. 1942. Bactericidal action of ultraviolet radiation on airborne microorganisms. J Bacteriol 44:85-94.
- Rice EW, Hoff JC. 1999. Inactivation of *Giardia lamblia* cysts by ultraviolet irradiation. Appl & Environ Microbiol 42(3):546-547.
- Riley RL, O'Grady F. 1961. Airborne Infection. New York: The Macmillan Company.
- Riley RL, Kaufman JE. 1972. Effect of relative humidity on the inactivation of airborne *Serratia marcescens* by ultraviolet radiation. Applied Microbiology 23(6):1113-1120.
- Riley RL. 1972. The ecology of indoor atmospheres: Airborne infection in hospitals. J Chron Dis 25:421-423.
- Riley RL, Knight M, Middlebrook G. 1976. Ultraviolet susceptibility of BCG and virulent tubercle bacilli. Am Rev Resp Dis 113:413-418.
- Riley RL, Nardell EA. 1989. Clearing the air: The theory and application of ultraviolet disinfection. Am Rev Resp Dis 139:1286-1294.
- Rohsenow WM, Hartnett JP. 1973. Handbook of Heat Transfer. New York: McGraw-Hill.
- Russell AD. 1982. The destruction of bacterial spores. New York: Academic Press.
- Sako H, and Sorimachi, M. 1985. Susceptibility of fish pathogenic viruses, bacteria and fungus to ultraviolet radiation and the disinfectant effect of U.V.-ozone water sterilise on the pathogogens in water. Bull Nat Res Inst Aquacult 8:51-58.
- Scheir R, Fencil FB. 1996. Using UVC Technology to Enhance IAQ. HPAC Feb.
- Schoenen D, Kolch A, Gebel J. 1993. Influence of geometrical parameters in different irradiation vessels on UV disinfection rate. Zbl Hyg Umweltmed 194(3):313-320.
- Seagal-Maurer S, Kalkut GE. 1994. Environmental control of tuberculosis: Continuing controversy. Clinical Infectious Diseases 19:299-308.
- Setlow JK. 1966. Photoreactivation. Radiat Res Suppl 6:141-155.
- Severin BF, Suidan MT, Englebrecht RS. 1983. Kinetic modeling of U.V. disinfection of water. Water Res 17(11):1669-1678.
- Severin BF, Suidan MT, Englebrecht RS. 1984. Mixing effects in UV disinfection. J Water Pollution Control Federation 56(7):881-888.
- Severin BF. 1986. Ultraviolet disinfection for municipal wastewater. Chemical Engineering Progress 81:37-44.
- Severin BF, Roessler PF. 1998. Resolving UV photometer outputs with modeled intensity profiles. Wat Res 32(5):1718-1724.
- Shama G. 1992. Inactivation of *Escherichia coli* by ultraviolet light and hydrogen peroxide in a thin film contactor. Letters in Appl Microb 15:259-260.

- Shama G. 1992. Ultraviolet irradiation apparatus for disinfecting liquids of high ultraviolet absorptivities. *Letters in Appl Microb* 15:69-72.
- Sharp DG. 1938. A quantitative method of determining the lethal effect of ultraviolet light on bacteria suspended in air. *J Bact* 35:589-599.
- Sharp G. 1939. The lethal action of short ultraviolet rays on several common pathogenic bacteria. *J Bact* 37:447-459.
- Sharp G. 1940. The effects of ultraviolet light on bacteria suspended in air. *J Bact* 38:535-547.
- Shaughnessy R, Levetin E, Rogers C. 1999. The effects of UV-C on biological contamination of AHUs in a commercial office building: Preliminary results. *Indoor Environment '99*:195-202.
- Sommer R, Cabaj A, Schoenen D, Gebel J, Kolsch E, Havalaar AH. 1995. Comparison of three laboratory devices for UV-inactivation of microorganisms. *Wat Sci Technol* 31:147-156.
- Sparrow EM, Cess RD. 1997. *Radiation Heat Transfer*. Belmont: Brooks/Cole Publ.
- Spendlove JC, Fannin KF. 1983. Source, significance, and control of indoor microbial aerosols: Human health aspects. *Public Health Reports* 98(3):229-244.
- Steril-Aire I. 2000. UVC lights save on energy while cleaning coils. *HPAC Engineering* 72(1):131-132.
- Suidan MT, Severin BF. 1986. Light intensity models for annular UV disinfection reactors. *AIChE Journal* 32(11):1902-1909.
- Sylvania. 1981. *Sylvania Engineering Bulletin 0-342, Germicidal and Short-Wave Ultraviolet Radiation*. : GTE Products Corp.
- Takahashi N. 1990. Ozonation of several organic compounds having low molecular weight under ultraviolet irradiation. *Ozone Science & Engineering* 12:1-17.
- Tamm I, Fluke DJ. 1950. The effect of monochromatic ultraviolet radiation on the infectivity and hemagglutinating ability of the influenza virus type A strain PR-8. *J Bact* 59:449-461.
- Taylor AR. 1960. Effects of nonionizing radiations of animal viruses. *Annals of the New York Academy of Sciences* 82:670-683.
- Thornsberry C, Balows A, Feeley J, Jakubowski W. *Legionella: Proceedings of the 2nd International Symposium; 1984; Atlanta*. American Society for Microbiology.
- Tothova L, Frankova E. 2001. The fungal spores elimination in drinking water by UV radiation. In: Fajzieva D, Brebbia CA, editors. *Environmental Health Risk*. Southampton: WIT Press.
- UVDI. 1999. *Report on Lamp Photosensor Data for UV Lamps*. Valencia, CA: Ultraviolet Devices, Inc.
- VanOsdell D, Foarde K. 2002. *Defining the Effectiveness of UV Lamps Installed in Circulating Air Ductwork*. Arlington, VA: ARTI. Report nr ARTI-21CR/610-40030-01.
- Vincent JH. 1995. *Aerosol Science for Industrial Hygienists*. New York: Pergamon.

- Von Sonntag C. 1986. Disinfection by free radicals and UV-radiation. *Water Supply* 4:11-18.
- Walter CW. 1969. Ventilation and air conditioning as bacteriologic engineering. *Anesthesiology* 31:186-192.
- Wang Y, Casadevall A. 1994. Decreased susceptibility of melanized *Cryptococcus neoformans* to UV light. *Appl Microb* 60(10):3864-3866.
- Watson HE. 1908. A note on the variation of the rate of disinfection with change in the concentration of disinfectant. *J Hyg* 8:536.
- Weinberger S, Evenchick Z, Hertman I. 1983. Postincision steps of photoproduct removal in a mutant of *Bacillus cereus* 569 that produces UV-sensitive spores. *J of Bacteriol* 156(2):909-913.
- Weinberger S, Evenchick Z, Hertman I. 1984. Transitory UV resistance during germination of UV-sensitive spores produced by a mutant of *Bacillus cereus* 569. *Photochem & Photobiol* 39(6):775-780.
- Wells WF. 1955. *Airborne Contagion*. Sciences AotNAo, editor. New York: New York Academy of Sciences.
- Westinghouse. 1982. Booklet A-8968, Westinghouse Lighting Handbook. : Westinghouse Electric Corp., Lamp Div.
- Willmon TL, Hollaender A, Langmuir AD. 1948. Studies of the control of acute respiratory diseases among naval recruits. *Am J Hyg* 48:227-232.
- Woods JE. 1980. The animal Enclosure -- A microenvironment. *Lab Animal Sci* 30(2):407.
- Woods JE, Grimsrud DT, Boschi N. 1997. *Healthy Buildings / IAQ '97*. Washington, DC: ASHRAE.
- Xu P, Peccia J, Fabian P, Martyny JW, Fennelly KP, Hernandez M, Miller SL. 2003. Efficacy of ultraviolet germicidal irradiation of upper-room air in inactivating airborne bacterial spores and mycobacteria in full-scale studies. *Atmos Environ* 37:405-419.
- Zemke V, Schoenen D. 1989. UV disinfecting experiments with *E. coli* and actinometric determination of the irradiation intensity. *Zbl Hyg Umweltmed* 188(3-4):380-384.

## APPENDIX A: Microbial UV Rate Constants and D90 Doses

Microbe	Type	Media	RH %	UVGI k m <sup>2</sup> /J	D90 J/m <sup>2</sup>	Source
Acinetobacter	Bacteria	Water	100%*	0.00023	10964.7	Keller 1982
Adenovirus	Virus	Surface	-	0.0047	489.9	Rainbow 1973
Adenovirus	Virus	Air	-	0.055	41.9	Jensen 1964
Aeromonas	Bacteria	-	-	0.2031	11.3	Sako 1985
Aspergillus	Fungi	Air	-	0.0007	3289	Luckiesh 1946
Aspergillus amstelodami	Fungi	Air	67	0.000797	2890	Luckiesh 1949
Aspergillus amstelodami	Fungi	Surface	-	0.002063	1116	Luckiesh 1949
Aspergillus amstelodami	Fungi	-	-	0.003289	700	Jepson 1975
Aspergillus amstelodami	Fungi	Air	-	0.00344	669	Luckiesh 1946
Aspergillus flavus	Fungi	-	-	0.003838	600	Nagy 1964
Aspergillus fumigatus	Fungi	Surface	-	0.001028	2240	Chick 1963
Aspergillus fumigatus (vegetative)	Fungi	Surface	-	0.004112	560	Chick 1963
Aspergillus glaucus	Fungi	-	-	0.005233	440	Nagy 1964
Aspergillus niger	Fungi	Air	55	0.000128	17938	Luckiesh 1949
Aspergillus niger	Fungi	Surface	-	0.000385	5979	Luckiesh 1949
Aspergillus niger	Fungi	Surface	-	0.000514	4480	Chick 1963
Aspergillus niger	Fungi	-	-	0.001744	1320	Nagy 1964
Aspergillus niger	Fungi	-	-	0.002303	1000	Jepson 1975
Aspergillus niger	Fungi	Surface	-	0.00307	750	Gritz 1990
Aspergillus niger	Fungi	Surface	-	0.00731	315	Kowalski 2001
Aspergillus versicolor	Fungi	Air	55	0.003	768	vanOsdell 2002
Aspergillus versicolor	Fungi	Air	85	0.006	384	vanOsdell 2002
Bacillus anthracis spores	Bacteria	Surface	-	0.0031	742.8	Knudson 1986
Bacillus anthracis spores	Bacteria	-	-	0.028654	80.4	Jepson 1975
Bacillus anthracis spores	Bacteria	-	-	0.050942	45.2	Nagy 1964
Bacillus cereus spores	Bacteria	Surface	-	0.005638	408.4	Benoit 1990
Bacillus cereus spores	Bacteria	-	-	0.00863	266.8	Weinberger 1984
Bacillus cereus spores	Bacteria	Surface	-	0.010983	209.6	Weisova 1966
Bacillus cereus spores	Bacteria	Surface	-	0.019789	116.4	Germaine 1973
Bacillus subtilis (vegetative)	Bacteria	-	-	0.0324	71.1	IES 1981
Bacillus subtilis (vegetative)	Bacteria	-	-	0.0397	58	Nagy 1964
Bacillus subtilis (vegetative)	Bacteria	Water	100%*	0.0921	25.1	Lojo 1985
Bacillus subtilis (vegetative)	Bacteria	Air	-	0.168582	13.7	Nakamura 1987
Bacillus subtilis spores	Bacteria	Water	100%*	0.0136	171.8	Qualls 1983
Bacillus subtilis spores	Bacteria	-	-	0.015351	150	Chang 1985
Bacillus subtilis spores	Bacteria	-	-	0.019821	116.2	Sommer 1989
Bacillus subtilis spores	Bacteria	-	-	0.01985	116	Nagy 1964
Bacillus subtilis spores	Bacteria	Air	55-85	0.02	115.1	vanOsdell 2002
Bacillus subtilis spores	Bacteria	Surface	-	0.0203	113.4	Munakata 1972
Bacillus subtilis spores	Bacteria	Surface	-	0.0246	93.6	Rentschler 1941
Bacillus subtilis spores	Bacteria	Air	95	0.025	92.1	Peccia 2001
Bacillus subtilis spores	Bacteria	Water	100%*	0.0258	89.9	Homeck 1985
Bacillus subtilis spores	Bacteria	Air	50	0.027	85.3	Peccia 2001
Bacillus subtilis spores	Bacteria	Surface	-	0.0337	68.3	Munakata 1975
Bacillus subtilis spores	Bacteria	Air	45	0.0449	51.3	Kowalski 2001
Blastomyces dermatitidis (vegetative)	Fungi	Surface	-	0.016447	140	Chick 1963
Blastomyces dermatitidis (yeast)	Fungi	Surface	-	0.016447	140	Chick 1963
Burkholderia cenocepacia	Bacteria	Water	100%*	0.039563	58.2	Abshire 1981
Candida albicans (yeast)	Fungi	Surface	-	0.00307	750	Gritz 1990

## APPENDIX A: Microbial UV Rate Constants and D90 Doses

Microbe	Type	Media	RH %	UVGI k m <sup>2</sup> /J	D90 J/m <sup>2</sup>	Source
Candida albicans (yeast)	Fungi	Water	100%*	0.005151	447	Abshire 1981
Candida albicans (yeast)	Fungi	Surface	-	0.008224	280	Chick 1963
Candida albicans (yeast)	Fungi	-	-	0.01	230	Dolman 1989
Cladosporium	Fungi	Air	-	0.00384	600	Luckiesh 1946
Cladosporium herbarum	Fungi	Air	53	0.000856	2691	Luckiesh 1949
Cladosporium herbarum	Fungi	Surface	-	0.002818	817	Luckiesh 1949
Cladosporium herbarum	Fungi	Air	-	0.0037	622	Luckiesh 1946
Cladosporium herbarum	Fungi	-	-	0.004605	500	Jepson 1975
Cladosporium sphaerospermum	Fungi	Air	-	0.0016	1439	vanOsdell 2002
Cladosporium trichoides	Fungi	Surface	-	0.002056	1120	Chick 1963
Cladosporium trichoides (vegetative)	Fungi	Surface	-	0.004112	560	Chick 1963
Cladosporium wernecki (vegetative)	Fungi	Surface	-	0.004112	560	Chick 1963
Cladosporium wernecki spores	Fungi	Surface	-	0.000514	4480	Chick 1963
Clostridium perfringens	Bacteria	Surface	-	0.017	135.4	Jepson 1975
Clostridium tetani	Bacteria	-	-	0.046992	49	Jepson 1975
Corynebacterium diphtheriae	Bacteria	-	-	0.068326	33.7	Nagy 1964
Corynebacterium diphtheriae	Bacteria	Surface	-	0.0701	32.8	Sharp 1939
Coxiella burnetii	Bacteria	Water	100%*	0.1535	15	Little 1980
Coxsackievirus	Virus	Water	100%*	0.02	127.9	Hill 1970
Coxsackievirus	Virus	Water	100%*	0.026837	85.8	Havelaar 1987
Coxsackievirus	Virus	Air	-	0.111	20.7	Jensen 1964
Cryptococcus neoformans	Fungi	Surface	-	0.0167	138	Wang 1994
Cryptococcus neoformans (yeast)	Fungi	Surface	-	0.008224	280	Chick 1963
Curvularia lunata (vegetative)	Fungi	Surface	-	0.004112	560	Chick 1963
Echovirus	Virus	Water	100%*	0.0219	106.1	Hill 1970
Enterobacter cloacae	Bacteria	Water	100%*	0.021419	107.5	Martiny 1988
Enterobacter cloacae	Bacteria	Water	100%*	0.03598	64	Zemke 1990
Escherichia coli	Bacteria	Surface	-	0.010502	219.2	Luckiesh 1949
Escherichia coli	Bacteria	Water	100%*	0.028322	81.3	Abshire 1981
Escherichia coli	Bacteria	-	-	0.06524	35.3	Jepson 1975
Escherichia coli	Bacteria	-	-	0.076753	30	Nagy 1964
Escherichia coli	Bacteria	-	-	0.08009	28.7	Harm 1980
Escherichia coli	Bacteria	-	-	0.095941	24	David 1973
Escherichia coli	Bacteria	Air	-	0.156114	14.7	Luckiesh 1949
Francisella tularensis	Bacteria	Air	-	0.01474	156.2	Beebe 1959
Fusarium oxysporum	Fungi	Surface	-	0.008856	260	Asthana 1992
Fusarium solani	Fungi	Surface	-	0.007349	313	Asthana 1992
Fusarium spp. (vegetative)	Fungi	Surface	-	0.002056	1120	Chick 1963
Fusarium spp. spores	Fungi	Surface	-	0.004112	560	Chick 1963
Haemophilus influenzae	Bacteria	Surface	-	0.0599	38.4	Mongold 1992
Histoplasma capsulatum (vegetative)	Fungi	Surface	-	0.016447	140	Chick 1963
Histoplasma capsulatum (yeast)	Fungi	Surface	-	0.016447	140	Chick 1963
Influenza A virus	Virus	Air	-	0.119	19.3	Jensen 1964
Kilham Rat Virus (parvovirus)	Virus	-	-	0.095941	24	Proctor 1972
Klebsiella pneumoniae	Bacteria	Water	100%*	0.023616	97.5	Martiny 1988
Klebsiella pneumoniae	Bacteria	Water	100%*	0.0548	42	Zemke 1990
Legionella pneumophila	Bacteria	Water	100%*	0.122805	18.8	Yamamoto 1987
Legionella pneumophila	Bacteria	Water	100%*	0.192979	11.9	Gilpin 1985
Legionella pneumophila	Bacteria	Surface	-	0.248493	9.3	Antopol 1979

## APPENDIX A: Microbial UV Rate Constants and D90 Doses

Microbe	Type	Media	RH %	UVGI k m <sup>2</sup> /J	D90 J/m <sup>2</sup>	Source
Legionella pneumophila	Bacteria	Surface	-	0.446126	5.2	Knudson 1985
Listeria monocytogenes	Bacteria	Surface	-	0.03	76.8	Kim 2002
Listeria monocytogenes	Bacteria	Air	-	0.2303	10	Collins 1971
Micrococcus	Bacteria	-	-	0.028782	80	Nagy 1964
Micrococcus candidus	Bacteria	-	-	0.038059	60.5	IES 1981
Micrococcus sphaeroides	Bacteria	-	-	0.023026	100	IES 1981
Moraxella-Acinetobacter	Bacteria	Water	100%*	0.00022	10964.7	Keller 1982
Mucor	Fungi	Air	-	0.0135	171	Luckiesh 1946
Mucor mucedo	Fungi	Air	63	0.000924	2491	Luckiesh 1949
Mucor mucedo	Fungi	Surface	-	0.002962	777	Luckiesh 1949
Mucor mucedo	Fungi	-	-	0.003838	600	Jepson 1975
Mucor mucedo	Fungi	Air	-	0.00399	577	Luckiesh 1946
Mucor racemosus	Fungi	-	-	0.013545	170	Nagy 1964
Mucor spp. (vegetative)	Fungi	Surface	-	0.008224	280	Chick 1963
Mucor spp. spores	Fungi	Surface	-	0.016447	140	Chick 1963
Mycobacterium avium-intracellulare	Bacteria	Surface	-	0.040634	56.7	David 1973
Mycobacterium bovis BCG	Bacteria	Air	-	0.1055	21.8	Collins 1971
Mycobacterium bovis BCG	Bacteria	Air	-	0.19	12.1	Peccia 2002
Mycobacterium bovis BCG	Bacteria	Air	50	0.242	9.5	Riley 1976
Mycobacterium flaviscens	Bacteria	Surface	-	0.019188	120	David 1973
Mycobacterium fortuitum	Bacteria	Surface	-	0.046052	50	David 1973
Mycobacterium kansasii	Bacteria	Surface	-	0.035424	65	David 1973
Mycobacterium marinum	Bacteria	Surface	-	0.038808	59.3	David 1973
Mycobacterium parafortuitum	Bacteria	Water	100%*	0.01	287.8	Peccia 2001
Mycobacterium parafortuitum	Bacteria	Air	95	0.1	23	Peccia 2001
Mycobacterium parafortuitum	Bacteria	Air	-	0.12	19.2	Xu 2003
Mycobacterium parafortuitum	Bacteria	Air	50	0.17	13.5	Peccia 2001
Mycobacterium phlei	Bacteria	Surface	-	0.036357	63.3	David 1973
Mycobacterium phlei	Bacteria	Air	50	0.0365	63.1	Riley 1976
Mycobacterium phlei	Bacteria	Air	50	0.1	23	Kethley 1973
Mycobacterium phlei	Bacteria	Air	50	0.14	16.4	Gillis 1974
Mycobacterium smegmatis	Bacteria	Surface	-	0.030701	75	David 1973
Mycobacterium smegmatis	Bacteria	Air	50	0.19	12.1	Gillis 1974
Mycobacterium smegmatis	Bacteria	Surface	-	0.23	10	Boshoff 2003
Mycobacterium tuberculosis	Bacteria	Surface	-	0.086347	26.7	David 1973
Mycobacterium tuberculosis	Bacteria	Air	-	0.2132	10.8	Collins 1971
Mycobacterium tuberculosis	Bacteria	Surface	-	0.33	7	Boshoff 2003
Mycobacterium tuberculosis	Bacteria	Air	50	0.4721	4.9	Riley 1976
Neisseria catarrhalis	Bacteria	-	-	0.052331	44	Nagy 1964
Newcastle Disease Virus (NDV)	Virus	-	-	0.361835	6.4	vonBrodorotti 1982
Nocardia asteroides (vegetative)	Bacteria	Surface	-	0.008224	280	Chick 1963
Parvovirus (Bovine)	Virus	-	-	0.0658	35	vonBrodorotti 1982
Penicillium chrysogenum	Fungi	Air	41	0.001005	2292	Luckiesh 1949
Penicillium chrysogenum	Fungi	Air	-	0.0014	1645	vanOsdell 2002
Penicillium chrysogenum	Fungi	Surface	-	0.00361	638	Luckiesh 1949
Penicillium chrysogenum	Fungi	Air	-	0.00434	531	Luckiesh 1946
Penicillium chrysogenum	Fungi	-	-	0.005756	400	Jepson 1975
Penicillium digitatum	Fungi	-	-	0.005233	440	Nagy 1964
Penicillium digitatum	Fungi	Surface	-	0.00718	321	Asthana 1992

## APPENDIX A: Microbial UV Rate Constants and D90 Doses

Microbe	Type	Media	RH %	UVGI k m <sup>2</sup> /J	D90 J/m <sup>2</sup>	Source
<i>Penicillium digitatum</i>	Fungi	-	-	0.005233	440	Nagy 1964
<i>Penicillium digitatum</i>	Fungi	Surface	-	0.00718	321	Asthana 1992
<i>Penicillium expansum</i>	Fungi	-	-	0.017712	130	Nagy 1964
<i>Penicillium italicum</i>	Fungi	Surface	-	0.00718	321	Asthana 1992
<i>Penicillium roquefortii</i>	Fungi	-	-	0.017712	130	Nagy 1964
<i>Penicillium</i> spp. (vegetative)	Fungi	Surface	-	0.008224	280	Chick 1963
<i>Penicillium</i> spp. spores	Fungi	Surface	-	0.001028	2240	Chick 1963
<i>Proteus vulgaris</i>	Bacteria	-	-	0.076753	30	Nagy 1964
<i>Proteus vulgaris</i>	Bacteria	-	-	0.087219	26.4	IES 1981
<i>Pseudomonas aeruginosa</i>	Bacteria	-	-	0.041865	55	Zelle 1955
<i>Pseudomonas aeruginosa</i>	Bacteria	Water	-	0.0419	55	Antopol 1979
<i>Pseudomonas aeruginosa</i>	Bacteria	Water	100%*	0.066	36	Abshire 1981
<i>Pseudomonas aeruginosa</i>	Bacteria	Water	100%*	0.226921	10.1	Gilpin 1985
<i>Pseudomonas aeruginosa</i>	Bacteria	Air	-	0.2375	9.7	Collins 1971
<i>Pseudomonas aeruginosa</i>	Bacteria	Air	-	0.5721	4	Sharp 1940
<i>Pseudomonas diminuta</i>	Bacteria	Water	100%*	0.023911	96.3	Abshire 1981
<i>Pseudomonas fluorescens</i>	Bacteria	-	-	0.065788	35	Nagy 1964
<i>Pseudomonas fluorescens</i>	Bacteria	Air	-	0.935	2.5	vanOsdell 2002
<i>Pseudomonas maltophilia</i>	Bacteria	Water	100%*	0.032941	69.9	Abshire 1981
<i>Pseudomonas putrefaciens</i>	Bacteria	Water	100%*	0.026619	86.5	Abshire 1981
Reovirus	Virus	Water	100%	0.0132	174.4	Hill 1970
Reovirus	Virus	Water	100%	0.015082	152.7	Harris 1987 (Type 1)
Reovirus	Virus	-	-	0.033579	68.6	vonBrodorotti 1982
Rhizopus	Fungi	Air	-	0.00861	267	Luckiesh 1946
<i>Rhizopus nigricans</i>	Fungi	-	-	0.000768	3000	Jepson 1975
<i>Rhizopus nigricans</i>	Fungi	Air	62	0.001992	1156	Luckiesh 1949
<i>Rhizopus nigricans</i>	Fungi	-	-	0.002074	1110	Nagy 1964
<i>Rhizopus nigricans</i>	Fungi	Air	-	0.00861	267	Luckiesh 1946
<i>Rhizopus nigricans</i>	Fungi	Surface	-	0.0285	81	Kowalski 2001
<i>Rhizopus oryzae</i>	Fungi	Surface	-	0.000514	4480	Chick 1963
<i>Rhodotorula</i> spp. (yeast)	Fungi	Surface	-	0.002056	1120	Chick 1963
<i>Rickettsia prowazekii</i>	Bacteria	Surface	-	0.0292	78.9	Allen 1954
<i>Scopulariopsis brevicaulis</i>	Fungi	Air	79	0.000797	2890	Luckiesh 1949
<i>Scopulariopsis brevicaulis</i>	Fungi	Surface	-	0.002358	977	Luckiesh 1949
<i>Scopulariopsis brevicaulis</i>	Fungi	Air	-	0.00344	669	Luckiesh 1946
<i>Scopulariopsis brevicaulis</i>	Fungi	-	-	0.003542	650	Jepson 1975
<i>Serratia marcescens</i>	Bacteria	Water	100%*	0.01071	215	Martiny 1988
<i>Serratia marcescens</i>	Bacteria	Surface	-	0.02194	105	Harris 1993
<i>Serratia marcescens</i>	Bacteria	Air	95	0.065	35.4	Peccia 2001
<i>Serratia marcescens</i>	Bacteria	-	-	0.095148	24.2	Nagy 1964
<i>Serratia marcescens</i>	Bacteria	-	-	0.104663	22	Jepson 1975
<i>Serratia marcescens</i>	Bacteria	-	-	0.104663	22	Zelle 1955
<i>Serratia marcescens</i>	Bacteria	Air	-	0.1047	22	Sharp 1939
<i>Serratia marcescens</i>	Bacteria	Water	100%*	0.1049	22	Antopol 1979
<i>Serratia marcescens</i>	Bacteria	Air	-	0.1225	18.8	Rentschler 1941
<i>Serratia marcescens</i>	Bacteria	Air	-	0.2208	10.4	Collins 1971
<i>Serratia marcescens</i>	Bacteria	Air	25-57	0.2867	8	Kowalski 2001
<i>Serratia marcescens</i>	Bacteria	Air	60	0.2909	7.9	Peccia 2001
<i>Serratia marcescens</i>	Bacteria	Air	-	0.328941	7	Nakamura 1987

## APPENDIX A: Microbial UV Rate Constants and D90 Doses

Microbe	Type	Media	RH %	UVGI k m <sup>2</sup> /J	D90 J/m <sup>2</sup>	Source
<i>Serratia marcescens</i>	Bacteria	Air	-	0.4449	5.2	Sharp 1940
<i>Serratia marcescens</i>	Bacteria	Air	50	0.45	5.1	Peccia 2001
<i>Serratia marcescens</i>	Bacteria	Air	22-33	0.58	4	Ko 2000
<i>Serratia marcescens</i>	Bacteria	Air	-	0.749	3.1	vanOsdell 2002
<i>Serratia marcescens</i>	Bacteria	Water	100%*	2.093259	1.1	Lai 2004
<i>Serratia marcescens</i>	Bacteria	Air	60	3.289407	0.7	Riley 1972
<i>Serratia marcescens</i>	Bacteria	Air	30	6.39607	0.4	Riley 1972
<i>Serratia marcescens</i>	Bacteria	Air	45	8.223518	0.3	Riley 1972
Sindbis virus	Virus	-	-	0.038645	59.6	vonBrodorotti 1982
<i>Sporotrichum schenkii</i> (yeast)	Fungi	Surface	-	0.008224	280	Chick 1963
<i>Staphylococcus albus</i>	Bacteria	-	-	0.12514	18.4	Nagy 1964
<i>Staphylococcus aureus</i>	Bacteria	Surface	-	0.014441	159.5	Luckiesh 1949
<i>Staphylococcus aureus</i>	Bacteria	Water	100%*	0.041339	55.7	Abshire 1981
<i>Staphylococcus aureus</i>	Bacteria	Surface	-	0.085314	27	Chang 1985
<i>Staphylococcus aureus</i>	Bacteria	-	-	0.088561	26	Jepson 1975
<i>Staphylococcus aureus</i>	Bacteria	-	-	0.088561	26	Nagy 1964
<i>Staphylococcus aureus</i>	Bacteria	Surface	-	0.0886	26	Sharp 1939
<i>Staphylococcus aureus</i>	Bacteria	Surface	-	0.1184	19.4	Gates 1929
<i>Staphylococcus aureus</i>	Bacteria	Air	-	0.222163	10.4	Luckiesh 1949
<i>Staphylococcus aureus</i>	Bacteria	Air	-	0.3476	6.6	Sharp 1940
<i>Staphylococcus aureus</i>	Bacteria	Air	-	0.962	2.4	Luckiesh 1946
<i>Staphylococcus epidermis</i>	Bacteria	Water	100%*	0.014329	160.7	Harris 1993
<i>Staphylococcus epidermis</i>	Bacteria	Air	85	0.08	28.8	vanOsdell 2002
<i>Staphylococcus epidermis</i>	Bacteria	Air	55	0.24	9.6	vanOsdell 2002
<i>Streptococcus</i> (alpha)	Bacteria	Air	-	0.361014	6.4	Luckiesh 1949
<i>Streptococcus</i> (beta)	Bacteria	Air	-	0.100456	22.9	Luckiesh 1949
<i>Streptococcus faecalis</i>	Bacteria	Water	100%*	0.019188	120	Abshire 1981
<i>Streptococcus faecalis</i>	Bacteria	Surface	-	0.062744	36.7	Chang 1985
<i>Streptococcus faecalis</i>	Bacteria	Water	100%*	0.075398	30.5	Harris 1987
<i>Streptococcus hemolyticus</i>	Bacteria	-	-	0.106601	21.6	Nagy 1964
<i>Streptococcus lactis</i>	Bacteria	-	-	0.03744	61.5	Nagy 1964
<i>Streptococcus pneumoniae</i>	Bacteria	-	-	0.055	41.9	Chang 1985
<i>Streptococcus pyogenes</i>	Bacteria	-	-	0.104663	22	Jepson 1975
<i>Streptococcus pyogenes</i>	Bacteria	Surface	-	0.6161	3.7	Lidwell 1950
<i>Streptococcus viridans</i>	Bacteria	-	-	0.115129	20	Nagy 1964
<i>Torula bergeri</i> (vegetative)	Fungi	Surface	-	0.000514	4480	Chick 1963
<i>Trichophyton rubrum</i> (vegetative)	Fungi	Surface	-	0.004112	560	Chick 1963
<i>Trichophyton rubrum</i> spores	Fungi	Surface	-	0.004112	560	Chick 1963
<i>Ustilago zeae</i> (yeast)	Fungi	Surface	-	0.002056	1120	Chick 1963
<i>Ustilago zeae</i> spores	Fungi	-	-	0.0658	35	Sussman 1966
<i>Vaccinia virus</i>	Virus	-	-	0.127921	18	Klein 1994
<i>Vaccinia virus</i>	Virus	Air	-	0.1528	15.1	Collier 1955
<i>Vaccinia virus</i>	Virus	Air	-	0.153	15	Jensen 1964
<i>Vaccinia virus</i>	Virus	Surface	-	0.348877	6.6	Galasso 1965
<i>Varicella-zoster virus</i> (VZV)	Virus	-	-	0.05862	39.3	Lytle 1971 (Herpes)
<i>Yersinia enterocolitica</i>	Bacteria	-	-	0.081268	28.3	Carlson 1975
<i>Yersinia enterocolitica</i>	Bacteria	-	-	0.204674	11.3	Butler 1987

### Appendix B: Common Indoor Bacteria

PATHOGEN	GROUP	TYPE	DISEASE GROUP	BIOSAFETY LEVEL
Acinetobacter	Bacteria	Gram-	Endogenous	Risk Group 2
Actinomyces israelii	Bacteria	Gram+	Endogenous	Risk Group 2
Aeromonas	Bacteria	Gram-	Non-communicable	Risk Group 2
Alcaligenes	Bacteria	Gram-	Endogenous	Risk Group 2
Bacteroides fragilis	Bacteria	Gram-	Endogenous	Risk Group 2
Bordetella pertussis	Bacteria	Gram-	Communicable	Risk Group 2
Bruella	Bacteria	Gram-	Non-communicable	Risk Group 2-3
Burkholderia cepacia	Bacteria	Gram-	Non-communicable	Risk Group 1
Burkholderia mallei	Bacteria	Gram-	Non-communicable	Risk Group 3
Burkholderia pseudomallei	Bacteria	Gram-	Non-communicable	Risk Group 2-3
Cardiobacterium	Bacteria	Gram-	Endogenous	Risk Group 2
Chlamydia pneumoniae	Bacteria	Gram-	Communicable	Risk Group 2
Chlamydophila psittaci	Bacteria	Gram-	Non-communicable	Risk Group 2-3
Clostridium botulinum	Bacteria	Gram+	Non-communicable	Risk Group 2-4
Clostridium perfringens	Bacteria	Gram+	Non-communicable	Risk Group 2
Corynebacterium diphtheriae	Bacteria	Gram+	Communicable	Risk Group 2
Enterobacter cloacae	Bacteria	Gram-	Endogenous	Risk Group 1
Enterococcus	Bacteria	Gram+	Non-communicable	Risk Group 1-2
Enterococcus faecalis	Bacteria	Gram+	Endogenous	Risk Group 1
Francisella tularensis	Bacteria	Gram-	Non-communicable	Risk Group 2-3
Haemophilus influenzae	Bacteria	Gram-	Communicable	Risk Group 2
Haemophilus parainfluenzae	Bacteria	Gram-	Endogenous	Risk Group 2
Klebsiella pneumoniae	Bacteria	Gram-	Endogenous	Risk Group 2
Legionella pneumophila	Bacteria	Gram-	Non-communicable	Risk Group 2
Listeria monocytogenes	Bacteria	Gram+	Non-communicable	
Moraxella	Bacteria	Gram-	Endogenous	Risk Group 2
Mycobacterium avium	Bacteria	Gram+	Non-communicable	Risk Group 3
Mycobacterium kansasii	Bacteria	Gram+	Non-communicable	Risk Group 2
Mycobacterium tuberculosis	Bacteria	Gram+ (acid fast)	Communicable	Risk Group 2-3
Mycoplasma pneumoniae	Bacteria	no wall	Endogenous	Risk Group 2
Neisseria meningitidis	Bacteria	Gram-	Endogenous	Risk Group 2
Proteus mirabilis	Bacteria	Gram-	Endogenous	Risk Group 2
Pseudomonas aeruginosa	Bacteria	Gram-	Non-communicable	Risk Group 1
Rickettsia prowazeki	Bacteria	Gram-	Vector-borne	Risk Group 2-3
Rickettsia rickettsii	Bacteria	Gram-	Vector-borne	Risk Group 2-3
Salmonella typhi	Bacteria	Gram-	Food-borne	Risk Group 2
Serratia marcescens	Bacteria	Gram-	Endogenous	Risk Group 1
Shigella	Bacteria	Gram-	Food-borne	Risk Group 2
Staphylococcus aureus	Bacteria	Gram+	Endogenous	Risk Group 2
Staphylococcus epidermis	Bacteria	Gram+	Endogenous	Risk Group 1
Streptococcus pneumoniae	Bacteria	Gram+	Communicable	Risk Group 2
Streptococcus pyogenes	Bacteria	Gram+	Communicable	Risk Group 2
Vibrio cholerae	Bacteria	Gram-	Food-borne	Risk Group 2
Yersinia pestis	Bacteria	Gram-	Communicable	Risk Group 2-3
Coxiella burnetii	Bacteria / Rickettsiae	Gram-	Non-communicable	Risk Group 2-3
Bacillus anthracis	Bacterial Spore	Gram+	Non-communicable	Risk Group 2-3
Micromonospora faeni	Bacterial Spore	Micromonosporaceae	Non-communicable	-
Nocardia asteroides	Bacterial Spore	Nocardiaceae	Non-communicable	Risk Group 2
Nocardia brasiliensis	Bacterial Spore	Nocardiaceae	Non-communicable	Risk Group 2
Saccharopolyspora rectivirgula	Bacterial Spore	Micromonosporaceae	Non-communicable	Risk Group 2
Thermoactinomyces sacchari	Bacterial Spore	Micromonosporaceae	Non-communicable	Risk Group 2
Thermoactinomyces vulgaris	Bacterial Spore	Micromonosporaceae	Non-communicable	Risk Group 1
Thermomonospora viridis	Bacterial Spore	Micromonosporaceae	Non-communicable	Risk Group 1

### Appendix C: Common Indoor Fungi

PATHOGEN	GROUP	PHYLUM	DISEASE GROUP	BIOSAFETY LEVEL
Absidia	Fungal Spore	Zygomycetes	Non-communicable	Risk Group 2
Acremonium	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 1-2
Alternaria alternata	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 1
Arthrinium phaeospermum	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 2
Aspergillus	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 2
Aureobasidium pullulans	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 1
Blastomyces dermatitidis	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 2-3
Botrytis cinerea	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 3
Candida	Fungal Spore	Hyphomycetes	Endogenous	Risk Group 1
Chaetomium globosum	Fungal Spore	Ascomycetes	Non-communicable	Risk Group 1
Cladosporium	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 1
Coccidioides immitis	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 3
Cryptostroma corticale	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 2
Curvularia	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 1
Drechslera	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 2
Emericella nidulans	Fungal Spore	Ascomycetes	Non-communicable	Risk Group 1
Epicoccum nigrum	Fungal Spore	Ascomycetes	Non-communicable	Risk Group 1
Eurotium	Fungal Spore	Ascomycetes	Non-communicable	Risk Group 1
Exophiala	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 2
Fusarium	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 1
Helminthosporium	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 1
Histoplasma capsulatum	Fungal Spore	Ascomycetes	Non-communicable	Risk Group 3
Mucor plumbeus	Fungal Spore	Zygomycetes	Non-communicable	Risk Group 1
Paecilomyces variotii	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 1
Paracoccidioides	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 2
Penicillium	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 1
Phialophora	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 2
Phoma	Fungal Spore	Coelomycetes	Non-communicable	Risk Group 1
Pneumocystis carinii	Fungal Spore	Protozoal	Communicable	Risk Group 1
Rhizomucor pusillus	Fungal Spore	Zygomycetes	Non-communicable	Risk Group 1
Rhizopus stolonifer	Fungal Spore	Zygomycetes	Non-communicable	Risk Group 2
Rhodoturula	Fungal Spore	Blastomycetes	Non-communicable	-
Scopulariopsis	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 2
Sporothrix schenckii	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 2
Stachybotrys chartarum	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 1-2
Trichoderma	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 1
Trichophyton	Fungal Spore	Hyphomycetes	Non-communicable	
Ulocladium	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 1
Ustilago	Fungal Spore	Basidiomycetes	Non-communicable	Risk Group 1
Verticillium	Fungal Spore	Hyphomycetes	Non-communicable	
Wallemia sebi	Fungal Spore	Hyphomycetes	Non-communicable	Risk Group 1
Cryptococcus neoformans	Fungal Yeast	Hyphomycetes	Non-communicable	Risk Group 2
Trichosporon cutaneum	Fungi/Yeast	Basidiomycetes	Non-communicable	

## Appendix D: Health Care Facility Cost Estimates -- Part 1

Category	Facility 1	Facility 2	Facility 3	Facility 4	Facility 5	Facility 6
General Facility						
Age	21 years	13 years	31 years	40 years	63 years	27 years
Area	193,200 SF	353,000 SF	294,619 SF	134,988 SF	1,000,000 SF	364,400 SF
No. Licensed Beds	149	247	228	108	345	401
Conditions	Good	Good	Poor	Adequate	Poor	Fair
Inpatient						
No. Staffed Beds	172	187	204	74	303	340
Private	38	110	0	10	0	0
Semi-private	84	57	0	44	0	401
Ward	7	7pr.+ 13 NICU	204	20	345	0
Total Admissions	6,864	7,890	6,088	2,637	12,154	21,246
Inpatient Days	30,880	44,513	31,553	15,287	87,354	99,503
Average Daily Census	83	122	149	39	239	273
Percent Occupancy	57	65	73	52	79	80
Routine Beds	108	131	108	54	176	331
Special Care	22	56	22	10	169	46
Nursery	26	44	26	0	0	42
Outpatient						
No. of Exam Rooms	57	124	12	38	190	62
Clinic Visits	110,232	119,399	118,234	61,181	257,795	98,897
Visits per exam room	1,934	1,592	9,852	1,610	1,357	1,595
List of Clinics	13	7	12	23	13	2
ER Visits	57,390	41,822	76,875	42,287	95,951	81,890
ER Treatment Rooms	16	7	26	10	80	20
Facility Needs	Space	Space	Space	Space	Space	Space, toilets
Area	13,205 SF	36,000 SF	51,000 SF	6,715 SF	53,540 SF	
Visits per Room	3,587	5,975	2,956	4,229	1,194	4,095
Clinical						
No. Operating Rooms	4	10	5	4	16	12
O.R. Cases	2,424	3,068	4,780	2,202	11,189	8,959
Cases per O.R.	606	307	956	550	699	747
No. Delivery Rooms	3	3	3	0	0	9
Live Births	948	1,638	1,603	0	0	3,579
Births per Room	316	546	534	0	0	398
No. X-Ray Rooms	9	13	8	6	37	12
X-Ray Equipment	See attached	See attached	See attached	See attached	See attached	See attached
Estimated # of air handlers	23	23	17	23	200	17
Facility Adequacy	Adequate	Adequate	Inadequate	Adequate	Inadequate	Adequate
Major Needs	Labor & Delivery, NICU		Labor & Delivery, NICU, MRI	ER, Clinic, Parking, Storage	New Facility	Space, Privacy, CT Scanner

## Appendix D: Health Care Facility Cost Estimates -- Part 2

Category	Facility 1	Facility 2	Facility 3	Facility 4	Facility 5	Facility 6	TOTALS
<b>ESTIMATED COSTS</b>							
Coil Irradiation	\$ 38,318.00	\$ 63,864.00	\$ 54,603.00	\$ 34,486.00	\$ 178,819.00	\$ 64,928.00	\$ 435,018.00
Duct Treatment	\$ 30,959.00	\$ 56,565.00	\$ 47,210.00	\$ 21,631.00	\$ 160,242.00	\$ 58,392.00	\$ 374,999.00
Operating Room	\$ 56,000.00	\$ 140,000.00	\$ 70,000.00	\$ 56,000.00	\$ 224,000.00	\$ 168,000.00	\$ 714,000.00
TOTAL COSTS	\$ 125,277.00	\$ 260,429.00	\$ 171,813.00	\$ 112,117.00	\$ 563,061.00	\$ 291,320.00	\$ 1,524,017.00
Annual Cost	\$ 20,044.32	\$ 41,668.64	\$ 27,490.08	\$ 17,938.72	\$ 90,089.76	\$ 46,611.20	\$ 243,842.72
ANNUAL MAINTENANCE							
ESTIMATED SAVINGS							
PATIENTS							
Nosocomial Infections	\$ 154,400.00	\$ 222,565.00	\$ 157,765.00	\$ 76,435.00	\$ 436,770.00	\$ 497,515.00	\$ 1,545,450.00
Operating Infections	\$ 12,120.00	\$ 15,340.00	\$ 23,900.00	\$ 11,010.00	\$ 55,945.00	\$ 44,795.00	\$ 163,110.00
Clinic Infections	\$ 220,464.00	\$ 238,798.00	\$ 236,468.00	\$ 122,362.00	\$ 515,590.00	\$ 197,794.00	\$ 1,531,476.00
STAFF							\$ -
Nosocomial Infections	3% reduction*	3% reduction*	3% reduction*	3% reduction*	3% reduction*	3% reduction*	\$ -
Health Care	20% reduction*	20% reduction*	20% reduction*	20% reduction*	20% reduction*	20% reduction*	\$ -
Illness Absentee rate	20% reduction*	20% reduction*	20% reduction*	20% reduction*	20% reduction*	20% reduction*	\$ -
COIL & DUCT CLEANING	\$ 1,725.00	\$ 1,725.00	\$ 1,275.00	\$ 1,725.00	\$ 15,000.00	\$ 1,275.00	\$ 22,725.00
ENERGY SAVINGS	10 - 14%*	10 - 14%*	10 - 14%*	10 - 14%*	10 - 14%*	10 - 14%*	\$ -
EXTENDED LIFE OF UNITS	10%*	10%*	10%*	10%*	10%*	10%*	\$ -
							\$ -
TOTAL SAVINGS YEAR 1	\$ 388,709.00	\$ 478,428.00	\$ 419,408.00	\$ 211,532.00	\$ 1,023,305.00	\$ 741,379.00	\$ 3,262,761.00
TOTAL SAVINGS YEAR 2	\$ 388,709.00	\$ 478,428.00	\$ 419,408.00	\$ 211,532.00	\$ 1,023,305.00	\$ 741,379.00	\$ 1,708,560.00
TOTAL SAVINGS YEAR 3	\$ 388,709.00	\$ 478,428.00	\$ 419,408.00	\$ 211,532.00	\$ 1,023,305.00	\$ 741,379.00	\$ 1,708,560.00
LIFETIME SAVINGS 10 YRS	\$ 3,887,090.00	\$ 4,784,280.00	\$ 4,194,080.00	\$ 2,115,320.00	\$ 10,233,050.00	\$ 7,413,790.00	\$ 32,627,610.00

Note: Above estimates are based on SSI rate of 3% (NNIS 2000) and an assumed nosocomial infection rate of 0.5% for airborne pathogens.

\*(Savings may vary based on local utility rates, age of equipment, and actual measured before and after results).

## **APPENDIX F: Reports from articles and new sources on UVC effectiveness for improving IAQ and realizing savings from reduced energy and maintenance costs**

A recent laboratory study has shown that ultraviolet (UV) light can effectively kill the Severe Acute Respiratory Syndrome (SARS) virus, according to FP Technologies. The company, an engineering firm that uses UV radiation to sterilize air and surfaces, designed the SARS testing. Tests were performed at ZeptoMetrix Inc., a biotechnology lab.<sup>1</sup>

Florida Hospital has been installing high-output ultraviolet C-band (UVC) lights in its air-handling units (AHUs), and found that this has reduced or, in some cases, eliminated coil-cleaning programs. The lights also offer IAQ and infection control benefits.

The air handler was essentially returned to its original performance specifications. The coil and drain pan areas have maintained their clean condition, and eliminating the necessity for routine cleaning.<sup>2</sup>

Exposing cooling coils to UVC will eventually kill all mold, and keep the drain pan clean, and keeping the coil clean will increase equipment efficiency, up to the design rating of the equipment.”<sup>3</sup>

PSO installed UV lights in 1996-97 to eliminate a persistent mold and IAQ problem in the majority of its HVAC systems. The firm found that, by bathing the coil and drain pan areas from the downstream side was able to eradicate the microbial growth and its related problems. The lights eliminated most of the customary coil cleaning maintenance. It translated into a big energy consumption reduction.”<sup>4</sup>

Placing a UV light close to the air conditioning coil can prevent microbes from breeding in this typically moist area, keeping the coil clean and preventing that yeasty odor that accompanies the growth of these microorganisms.<sup>5</sup>

UVC light can penetrate the cellular wall of a microbe and damage DNA. UVC renders bacteria and spores unable to spread. Application of UVC at a distance of 12 inches for 15 minutes resulted in a 74 percent spore count reduction as compared to the control sample.<sup>6</sup>

UVC lights can significantly reduce annual cleaning of evaporator coils and condenser coils and can significantly minimize the maintenance staff's exposure to a variety of chemicals.<sup>7</sup>

Sickness among office workers in industrialized countries could be reduced by using ultraviolet lamps to kill germs in ventilation systems. Ultraviolet germicidal irradiation, or UVGI, is sometimes used in hospital ventilation systems to disinfect the air but is rarely incorporated into office or other building ducts. In a study published this week in The Lancet medical journal, Canadian scientists found that the technique reduced overall worker sickness by about 20%, including a 40% drop in breathing problems. The cost of UVGI installations could prove cost-effective compared with the yearly losses from absenteeism.<sup>8</sup>

-----

In one example, after a few weeks of UVC operation, static pressure over the coil decreased from 1.8 in.wg to just 0.7 in. wg. Air velocity over the coil more than doubled, from 230 fpm to 520 fpm. The coil and drain pan areas had no visible evidence of mold. The air exit wet bulb temperature decreased significantly, from 57° F (before UVC) to 53° (with UVC). It was estimated a total of \$4,867 in savings accrued for this one unit. This hospital is saving approximately 15% in HVAC energy costs. Results from this and other studies indicate that just a one-micron buildup of dirt or debris on coil surfaces can lead to a 15% loss in efficiency.

The ability of UVC to inactivate all types of bacteria and viruses is well documented. And, by destroying microbes trapped on cooling coils or in air filters, UVC light may increase the service life of these components and may facilitate safer changeout.<sup>9</sup>

---

<sup>1</sup> Testing Shows UV Effective At Killing SARS Virus /08/16/2004

<sup>2</sup> Retrofits Boost IAQ, Save Energy /Barb Checket-Hanks / Service, Maintenance and Troubleshooting Editor /08/16/2004

<sup>3</sup> Mechanical Inspectors Learn From IAQ Pro /by John R. Hall / Business Management Editor /09/24/2004

<sup>4</sup> UV technology sheds light on IAQ problems. Ultraviolet lights clear the air, reduce costs. /07/01/2000

<sup>5</sup> Contractor puts UV lighting system to the test. /by Ed Bas / Special Editor. /08/03/2000

<sup>6</sup> UVC Light: A Tool For Fighting Airborne Contaminants. /by John R. Hall / Business Management Editor. /07/17/2002

<sup>7</sup> IAQ Where We Work, Shop, And Save. /by Barb Checket-Hanks / Service/Maintenance and Troubleshooting Editor. /03/14/2003

<sup>8</sup> UV Lamps could reduce worker sickness. LONDON (AP) /11/28/2003

<sup>9</sup> UVC: Florida Hospital Puts HVAC Maintenance Under A New Light. Firouz Keikavousi - a mechanical engineer in charge of facilities management for Florida Hospital. /02/24/2004