Chapter 18

Commercial Buildings

18.1 Introduction

Applications for UVGI systems in commercial buildings vary with the type of building, but virtually every type of building can benefit from the use of in-duct air disinfection and many buildings can benefit from the use of other types of UV systems. The health hazards and microbiological problems associated with various types of commercial buildings are often unique to the type of facility. The problem of air quality is paramount in commercial office buildings while the problem of biocontamination is of the highest concern in the food industry. Other types of buildings have their own microbial concerns and even their own standards. The pharmaceutical industry has the highest aerobiological air quality standards (and lowest airborne microbial levels) while the other extreme, the agricultural industry, has the highest airborne microbial levels and unique aerobiological concerns. The individual problems of these facilities are addressed in the following sections, and industry experience relating to UV applications are discussed, along with recommendations for how UV systems can be applied. The specific types of UVGI systems are described in previous chapters and these should be referred to for detailed information on such applications.

18.2 Office Buildings

Commercial buildings are the single largest and most common type of building in the United States today, in terms of total floor area. Many common respiratory infections are regularly transmitted inside these structures due to daily occupancy and the extensive interaction of people within office buildings. Proximity and duration of exposure are major factors in the transmission of respiratory infections between office workers (Lidwell and Williams 1961). The risk of catching the common cold is increased by shared office space (Jaakkola and Heinonen 1995). Tuberculosis has also been show to transmit in office buildings between co-workers (Kenyon et al.

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2000). An association between respiratory tract symptoms in office workers and exposure to fungal and house dust mite aeroallergens was established by Menzies et al. (1998). The recent appearance of SARS virus highlights the susceptibility of office workers to the spread of airborne viruses (Yu et al. 2004). Sick Building Syndrome (SBS), often referred to as Building Related Illness (BRI) is a general category for a number of ailments, allergies, and complaints that are due to low levels of pollutants, synthetic irritants, fungi, bacteria or other factors that cause reactions in a certain fraction of building occupants (Lundin 1991).

Office buildings become contaminated with microbes brought in with the outside air as well as microbes that hail from indoor sources, including the occupants themselves. Accumulation of microbes on the cooling coils and ductwork can contribute to indoor air quality problems (Fink 1970). The aerobiology of office buildings can depend on both indoor sources (i.e. occupancy and cleanliness) as well as the composition and concentration of microbes in the outdoor air. Environmental microbes can enter via the ventilation system, via occupants (i.e. on clothes and shoes), and infiltration, especially from high-traffic lobbies that are under high negative pressure. Office buildings provide an environment that sustains microorganisms long enough for them to transmit infections to new hosts, or sometimes allows them to persist indefinitely, as in the case of fungal spores (Kowalski 2006). The indoor airborne concentrations of bacteria and fungi increase with the presence of occupants, due to the fact that people release bacteria continuously and also because human activity stirs up dust that may contain fungi and bacteria. Sessa et al. (2002) measured average office airborne concentrations of 493 cfu/m^3 for bacteria and 858 cfu/m^3 for fungi while levels were about four times lower when there were no occupants.

Most office buildings use dust filters in the MERV 6–8 range to filter outdoor or recirculated air but these have a limited effect on reducing fungal spores, bacteria, and viruses. Increasing filtration efficiency is one possible solution but retrofitting MERV filters in the 9–13 range, which can be highly effective against most airborne pathogens and allergens, may be difficult in most buildings because of increased pressure losses and possible reduction in airflow (Kowalski and Bahnfleth 2002). A suitable alternative to replacing filters is to add UV systems in the ductwork, which will not necessarily have any impact on airflow or pressure drop (see Fig. 18.1). In-duct UVGI is the most economic approach to disinfecting the air of commercial office buildings provided there is space in the ventilation system.

The economics of in-duct air disinfection can be greatly improved by locating the UV lamps at or around the cooling coils, thereby disinfecting the coils and improving their heat transfer capabilities. Cooling coils can first be steam cleaned to remove biological contamination and then a UVGI system can be added to continuously irradiate the coils. This not only prevents existing microbial growth but will tend to restore cooling coils to their original design operating level of performance, thereby saving energy costs (Kelly 1999).

Another alternative for improving air quality in office buildings and reducing the incidence of disease transmission between office workers is to locate recirculating UV units or Upper Room systems around the building to deal with local problems.

Fig. 18.1 In-duct UVGI system retrofit into an existing ventilation duct. System consists of four modular axial UV lamp fixtures. Photo courtesy of Virobuster Electronic Air Sterilization, Marthalaan, The Netherlands

Lower Room systems may also be used to control microbial contamination at floor level, especially in hallways or lobbies that see heavy foot traffic. Other applications of UVGI in office buildings may include overnight decontamination of kitchens, bathrooms, and storage areas with UV area disinfection units.

UVGI may not be a complete solution to aerobiological problems if the cause is due to some other factor like moisture or water damage. For more detailed information on dealing with air quality problems in office buildings see Kowalski (2006).

18.3 Industrial Facilities

Industrial facilities cannot be generalized in terms of the types of respiratory diseases to which workers may be subject because of their wide variety. Industrial facilities that handle organic materials have greater microbiological hazards while those that process inorganic products usually have less microbial hazards and more pollution hazards. Pollution, however, is a contributing factor in infectious diseases, including respiratory diseases. There are many types of occupational diseases, including asthma, and allergic reactions or hypersensitivity pneumonitis, which are not necessarily due to microbiological causes. Air disinfection systems that use UV have little or no effect on non-microbiological contaminants but if pathogens or allergens are the cause of the problem then UV systems may be applied to reduce the hazard.

Airborne particulate dust in industrial environments may contain organic materials, chemicals, microbes, biological compounds, or inert materials, and form a substrate on which microbes can grow. Allergen-bearing airborne particulates are causative agents of lung inflammation via their immunotoxic properties and can induce inflammatory alveolitis (Salvaggio 1994). Occupational asthma occurs in

2–6% of the asthmatic population and respiratory infection can be a predisposing factor for occupational asthma (Bardana 2003). Workers who clean or enter rarely-used rodent infested structures may be at increased risk of exposure to rodent-borne viruses such as hantavirus (Armstrong et al. 1995). Industries that process wood or paper, or that make use of paper products, have airborne allergen hazards since cellulose provides a nutrient source for a variety of allergenic fungi. Microbiological sampling in furniture factories found the most common airborne microorganisms included *Corynebacterium*, *Arthrobacter, Aspergillus*, *Penicillium*, and *Absidia* (Krysinska-Traczyk et al. 2002). Microbiologial studies of the air in sawmills were conducted by Dutkiewicz et al. (1996), who found that the most common organisms were *Arthrobacter, Corynebacterium, Brevibacterium*, *Microbacterium*, *Bacillus* spp., Gram-negative bacteria (*Rahnella*) and filamentous fungi (*Aspergillus, Penicillium*). Inhalation anthrax and cutaneous anthrax still occur occasionally in the textile industry. In a mill in the USA where outbreaks had occurred, anthrax levels were measured at up to 300 cfu/m^3 (Crook and Swan 2001). Q fever, which can result from inhalation or exposure to *Coxiella burnetti,* has been reported among workers in a wool and hair processing plant (Sigel et al. 1950).

Tuberculosis continues to be an occupational hazard in some parts of the world and is a growing problem elsewhere because of multi-drug resistance. In a study at Russian plants by Khudushina et al. (1991) the incidence of tuberculosis was highest at a foundry plant at 39.9 per 100,000 workers and in an automatic-assembly plant at 64.4 per 100,000 workers. Health care workers, prison guards, and prison inmates may all be at higher risk for tuberculosis. A one-year prospective study of inmates in Geneva showed that the prevalence of active and residual tuberculosis is 5–10 times higher among prisoners than in the general population (Chevallay et al. 1983). Many prisons in the US incorporate filtration and UVGI systems to help control tuberculosis transmissions.

Occasional outbreaks of Legionnaire's disease have continued to be sporadically reported in the work environment, including a large outbreak among exhibitors at a floral trade show where a whirlpool spa was on display (Boshuizen et al. 2001). Water damage in any building increases the risk of workers to allergens if fungal mold growth has occurred. Trout et al. (2001) documented extensive fungal contamination, including *Penicillium, Aspergillus*, and *Stachybotrys,* in a water-damaged building.

Control measures for aerobiological contamination in the workplace are similar to those for any buildings in general, including improved air filtration, improved air distribution, and increased outside air combined with energy recovery systems. The use of UVGI for air disinfection can have positive benefits for almost any type of industrial building depending on the nature of the problem. In-duct UV air disinfection systems are likely to be the most economic recourse since they provide centralized control of the air quality, and can simultaneously be applied to the cooling coils (in most applications) to save energy while disinfecting the air. The use of local recirculation units can aid in resolving local microbial contamination problems, and both Upper and Lower Room UVGI systems can be used to control biocontamination.

18.4 Food Industries

The food industry comprises food and beverage processing facilities, food handling industries, food storage facilities other than agricultural, and kitchens in the restaurant and hospitality industry. There are at least four types of potential health hazards associated with food handling – foodborne human pathogens, spoilage microbes, microbial allergens, and food allergens. Foodborne pathogens are generally transmitted by the oral route and almost exclusively cause stomach or intestinal diseases but some foodborne pathogens may be airborne at various stages of processing, storage, cooking, or consumption. The processing and handling of foods may also create opportunities for airborne mold spores to germinate and grow, resulting in secondary inhalation hazards. Applications for UVGI in the food industry include both air and surface disinfection, including surface disinfection of packaging materials and food handling equipment. UV has been used for air and surface disinfection in cheese plants, bakeries, breweries, meat plants, for food preservation, and for the decontamination of conveyor surfaces, and packaging containers (Koutchma 2008). One of the earliest applications of UV in the food industry involved the use of bare UV lamps to irradiate surfaces in the brewing and cheese making industries to control mold (Philips 1985). Liquid food disinfection with UV has been approved by the FDA but although UV has been highly effective for water disinfection, successful applications in disinfecting other liquids depends on the transmissivity of the liquid.

The direct disinfection of food by UV is generally only effective in cases where only the surface of foodstuffs requires disinfection since UV has limited penetrating ability (FDA 2000, Yaun and Summer 2002). Some foods can be effectively disinfected of certain food spoilage microbes, and UV is most effective on food products that have smooth and clean surfaces (Shama 1999, Seiler 1984). UV irradiation can significantly reduce the mold population on shells of eggs in only 15 min (Kuo et al. 1997). Studies have demonstrated that UV can reduce levels of *E. coli* and *Salmonella* on pork skin and muscle, *Listeria* on chicken meat, and *Salmonella* on poultry (Wong et al. 1998, Kim et al. 2001, Wallner-Pendleton et al. 1994). Begum et al. (2009) demonstrated that UV irradiation can inactivate food spoilage fungi like *Aspergillus, Penicillium*, and *Eurotium* but that the type of surface impacted the degree of disinfection. Marquenie et al. (2002) showed that *Botrytis cinerea* and *Monilinia fructigena*, two major post-harvest spoilage fungi of strawberries and cherries, could be reduced 3–4 logs by UV irradiation by doses of about 1000 J/m^2. Stevens et al. (1997) reported that UV could effectively reduce the incidence of storage rot disease on peaches due to *Monilinia fructicola*, reduce green mold (*Penicillium digitatum*) on tangerines, and reduce soft rot due to *Rhizopus* on tomatoes and sweet potatoes. Liu et al. (1993) showed that tomato diseases caused by *Alternaria alternata, Botrytis cinerea*, and *Rhizopus stolonifer* were effectively reduced by UV treatment. Hidaka and Kubota (2006) demonstrated a 90% reduction of *Aspergillus* and *Penicillium* species on the surfaces of wheat grain. Seiler (1984) reported increases in mold-free shelf life of clear-wrapped bakery products after moderate levels of UV exposure. Treatment of baked loaves in UV conveyor belt tunnels resulted in significantly increased shelf life (Shama 1999). Valero et al. (2007) found that UV irradiation of harvested grapes could prevent germination of fungi during storage or the dehydration process for raisins, using exposure times of up to 600 s.

One specialized application of UV in the food industry involves overhead tank disinfection, in which the airspace at the top of a liquid storage tank is disinfected by UV to control bacteria, yeast, and mold spores. Condensation of vapors in the head space of tanks, such as sugar syrup tanks, can produce dilute solutions on the liquid surface that provide ideal conditions for microbial growth. Two types of tank top systems are in use – systems which draw the air through a filter and UV system and return sterilized air to the tank space, and systems in which UV lamps are located directly in the head space of the tank and irradiate the liquid surface and internal tank surfaces. See Fig. 6.6 in Chap. 6 for an example of an overhead tank UV system.

Foodborne and waterborne pathogens represent the largest group of microorganisms that present health hazards in the food industry. In general, these do not present inhalation hazards, only ingestion hazards. However, some of these microbes can become airborne during processing and settle on foods, thereby becoming amenable to control by UV air and surface disinfection systems. Modern foodborne pathogens are often uniquely virulent and hazardous, like *Salmonella* and *Shigella*, which are contagious and depend on either on excretion in feces or vomiting to facilitate epidemic spread. Some agents of food poisoning, like *Staphylococcus* and *Clostridium*, are opportunistic or incidental contaminants of foods. Many molds like *Aspergillus* and *Penicillium* are common contaminants of the outdoor and indoor air that can grow on food and although they are not food pathogens they are potential inhalation hazards for food industry workers. Foodborne pathogens are predominantly bacteria but one virus has recently emerged and joined this class, Norwalk virus. Norwalk virus is a waterborne pathogen and has caused outbreaks on cruise ships (Marks et al. 2000). Food spoilage microbes are less of a health hazard than they are a nuisance in the food industry because of the damage they can cause to processed food (Samson et al. 2000). A wide variety of yeasts may also be causes of spoilage.

Table 18.1 lists the most common foodborne and waterborne pathogens in the food industry along with the type of hazard they present – pathogenic, toxic, allergenic, or spoilage. Many of the species listed in Table 18.1 have UV rate constants as given in Appendices A, B, and C. Virtually all of the fungal spores listed in Appendix C are potential contaminants in the food industry. Toxins produced by microbes may be endotoxins, exotoxins, or mycotoxins, and these will grow only if the conditions (moisture, temperature, etc.) are right. The key to controlling these toxins is to control microbial growth and to control the concentration of microbes in the surrounding areas. Ambient microbial levels can be controlled by food plant sanitation, adequate ventilation, and by various UV air disinfection technologies.

Table 18.1 Major microbial hazards in the food industry

Microbe	Type	Food class or source	Pathogen	Toxin	Allergen	Spoilage
Acinetobacter	Bacteria	various, humans	Yes	No	No	No
Aeromonas	Bacteria	various, humans	Yes	Yes	No	No
Alcaligenes	Bacteria	protein-rich	Yes	No	No	Yes
Aspergillus	Fungal spore	Grains, Vegetables, Meat	Yes	Yes	Yes	Yes
Bacillus cereus	Bacterial spore	various, environment	Yes	Yes	No	No
Botrytis	Fungal spore	Fruits, Vegetables, Meat	No	No	Yes	Yes
Brucella suis	Bacteria	various, humans	Yes	No	No	No
Campylobacter	Bacteria	various, humans	Yes	No	No	No
Cladosporium	Fungal spore	Dairy, Vegetables, Meat	Yes	Yes	Yes	Yes
Clostridium botulinum	Bacterial spore	various, humans	Yes	Yes	No	No
Clostridium perfingens	Bacterial spore	various, humans	Yes	Yes	No	No
Colletotrichum	Fungal spore	Fruits, Vegetables,	No	–	No	Yes
Corynebacterium	Bacteria	various, humans	Yes	No	No	Yes
Coxiella	Bacteria	various, humans	Yes	No	No	No
Cryptosporidium	Protozoa	various, humans	Yes	No	No	No
Cyclospora	Protozoa	various, environment	Yes	No	No	No
Diplodia	Fungal spore	Fruits, Vegetables,	No	–	No	Yes
Enterobacter	Bacteria	various, humans	Yes	Yes	No	No
Escherichia coli	Bacteria	various, humans	Yes	Yes	No	No
Fusarium	Fungal spore	Cereal, Fruits, Vegetables	No	Yes	Yes	Yes
Geotrichum	Fungal spore	Dairy,	No	No	No	Yes
Klebsiella pneumoniae	Bacteria	various, humans	Yes	Yes	No	No
Listeria	Bacteria	various, humans	Yes	No	No	No
Monila	Fungal spore	Grains, Dairy, Veg., Meat	No	–	No	Yes
Moraxella	Bacteria	various, humans	Yes	No	No	No
Mucor	Fungal spore	Grains, Fruits, Veg., Meat	Yes	No	Yes	Yes
Norwalk virus	Virus	various, humans	Yes	No	No	No
Oospora	Fungal spore	Dairy, Vegetables, Meat	No	–	No	Yes

Table 18.1 (continued)

Microbe	Type	Food class or source	Pathogen	Toxin	Allergen	Spoilage
Penicillium	Fungal spore	Grains, Dairy, Fruits, Veg.	No	Yes	Yes	Yes
Phomopsis	Fungal spore	Fruits, Vegetables	No	–	No	Yes
Phytophthora	Fungal spore	Fruits, Vegetables	No	–	No	Yes
Pseudomonas	Bacteria	various	Yes	No	No	Yes
Rhizopus	Fungal spore	Grains, Fruits, Veg., Meat	Yes	No	Yes	Yes
Salmonella	Bacteria	various, humans	Yes	Yes	No	No
Sclerotinia	Fungal spore	Fruits, Vegetables	No	–	No	Yes
Serratia	Bacteria	various, humans	Yes	No	No	Yes
Shigella	Bacteria	various, humans	Yes	Yes	No	No
Sporotrichum	Fungal spore	Bakery, Meat	No	–	Yes	Yes
Staphylococcus aureus	Bacteria	various, humans	Yes	No	No	No
Streptococcus	Bacteria	various, humans	Yes	No	No	No
Streptococcus suis	Bacteria	various, humans	Yes	No	No	No
Thamnidium	Fungal spore	Meat,	No	–	Yes	Yes
Trichoderma	Fungal spore	Fruits, Vegetables	No	Yes	Yes	Yes
Vibrio	Bacteria	various, humans	Yes	Yes	No	No
Yersinia enterolitica	Bacteria	various, humans	Yes	No	No	No

Most common food spoilage microbes have the capacity to transport in the air and therefore they are controllable to some degree by ventilation and by UV air disinfection systems. Evidence exists to suggest *Listeria monocytogenes*, a cause of many recent outbreaks, can settle on foodstuffs via the airborne route (1998). Studies indicate that *Salmonella* can survive in air for hours (Stersky et al. 1972). If air is recirculated through plant ventilation systems, organic material may accumulate inside ductwork and on air handling equipment, where fungi and bacteria may grow (1998). Air filtration can go along way towards controlling the amount of organic debris that accumulates, but UV is an ideal technology for use in controlling microbial and fungal growth inside air handling units, ductwork, and on cooling coils.

Concerns about the breakage of bare UV lamps and mercury hazards has led to new lamps that are sealed in an unbreakable plastic coating, such as shown in Fig. 18.2.

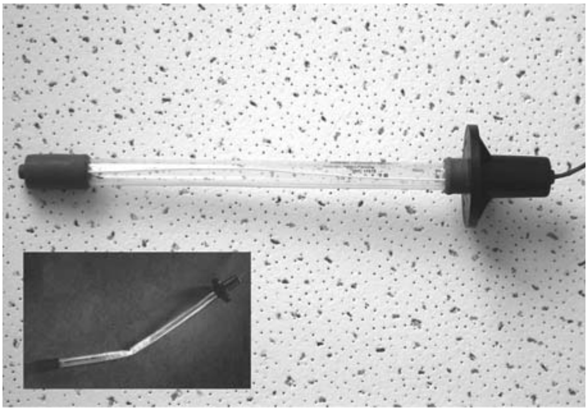

Fig. 18.2 Example of a waterproof, shatterproof UV lamp suitable for food industry applications. Insert shows a broken lamp in which the glass and mercury are fully contained by the plastic enclosure. Images courtesy of UVC Manufacturing and Consulting, Inc., Minden, NV

Mold and biofilms can develop on surfaces and equipment in the food and beverage industry, including tanks and vats, cooking equipment, walls and floors, and cooling coils (Carpentier and Cerf 1993). In general, standard cleaning and disinfection procedures are adequate to contain these problems but alternatives are available, including antimicrobial coatings like copper. UV irradiation of food processing equipment and surfaces, cooling coil disinfection systems, whole-area UV disinfection, and after-hours irradiation of rooms when personnel are not present are all viable options for maintaining high levels of disinfection in food industry facilities (Philips 1985, Kowalski and Dunn 2002). UV air disinfection systems may also be useful in controlling airborne hazards that result from hazards are created by industrial food processes that forcibly aerosolize contaminants. Pulsed UV light has seen increasing application in the food industry because of its rapid disinfection capabilities – see Chap. 16 for more information.

18.5 Educational Facilities

Educational facilities for children and students are focal points for disease transmission and as such they are ideally suited to UV applications that inhibit the transmission of contagious diseases. The concentration of young people in rooms causes cross-infections when even a single child comes to school with an infection such as a cold or a flu. Inevitably children who attend school bring home contagious infections which are then transmitted to family members, thereby continuing the process of epidemic spread in the community.

There are basically five types of educational facilities for children and students: Day Care centers, Preschools or Kindergartens, Elementary schools, Middle or High schools, and Colleges and Universities. Each type of facility and age group is subject to particular types on infections. Day care centers or nursery schools are commonly subject to high rates of Adenovirus, Echovirus, and Rhinovirus infections. Preschools or Kindergartens are commonly subject to upper respiratory infection (URI) outbreaks caused by Influenza, *Chlamydia*, and *Mycoplasma*. Elementary schools or Primary schools are commonly subject to outbreaks caused by *Bordetella*, Influenza, *Chlamydophila*, Mumps, Measles, *Mycoplasma*, Varicella-zoster, and *Streptococcus*. High schools and Military Academies are commonly subject to respiratory infections caused by Adenovirus, *Chlamydia*, Coxsackievirus, Influenza, *Mycobacterium tuberculosis*, and *Streptococcus* species. Colleges and Universities are commonly subject to outbreaks caused by Adenovirus, *Bordetella*, *Chlamydia*, Influenza, *Mycoplasma*, Parainfluenza, *Neisseria*, and *Streptococcus*. Medical schools and colleges have also been subject to outbreaks of Mumps and Respiratory Syncytial Virus (RSV). Table 18.2 summarizes many of the various common infections that have been associated with school facilities, with reference sources as indicated. Many of the microbes in Table 18.2 are susceptible to UV disinfection in air and on surfaces (see the UV rate constants for these species given in Appendix A).

Fungal spores also accumulate in schools and are responsible for a variety of respiratory illnesses including allergies and asthma. The most frequently encountered fungal taxa identified in a study of dust samples from twelve schools in Spain were *Alternaria, Aspergillus*, and *Penicillium* (Austin 1991).

Guidelines for ventilation air in school buildings are provided in ASHRAE Standard 62-2001 (ASHRAE 2001) but many schools do not meet the minimum recommendations either because the buildings are older or because of attempts to save energy costs due to endless budget cutting. One way to make up for the lack of ventilation air is to provide UV air disinfection systems, including Upper Room systems and in-duct UV systems.

A number of studies have been performed in schools to evaluate the effectiveness of UVGI systems on respiratory infections in schools. All of these studies involved Upper Room systems (see Chap. 9 for a summary of the results). Most of the studies produced a reduction of disease transmission with a net average reduction in respiratory infections of approximately 30%, and were effective against measles, mumps, varicella, chickenpox, cold viruses and other respiratory infections. Upper Room systems can be especially effective in classrooms that have little of no ventilation air and that have high ceilings. There are no studies that have addressed In-duct UVGI systems, which would be likely to prove even more effective if they were adequately designed.

18.6 Museums and Libraries

Materials and books that are kept in museums, libraries, and related archives may be both a source of allergens and a nutrient source for the growth of microorganisms, especially fungi. The growth of fungi and certain bacteria on stored materials contributes to biodeterioration, which is a major concern, and the aerobiology in

Table 18.2 Common pathogenic microbes in schools

Agent	Type	Disease	Type of school	Reference
Adenovirus	Virus	colds	Nursery school	Blacklow (1968)
		colds	College	Jackson (2000)
		colds	Medical school	Gerth (1987)
		URI	Naval Academy	Gray (2001)
Bordetella pertussis	Bacteria	whooping cough	Elementary	Gonzalez (2002)
		whooping cough	College	Jackson (2000)
Chlamydia pneumoniae	Bacteria	URI	Preschool/Elementary	Schmidt (2002)
		pneumonia	College	Jackson (2000)
		URI	Naval Academy	Gray (2001)
Coxsackievirus	Virus	pleurodynia	High school	Ikeda (1993)
Echovirus	Virus	colds	Nursery school	Hartmann (1967)
Herpes simplex	Virus	herpes simplex	College	McMillan (1993)
Influenza	Virus	flu	College	Jackson (2000)
		flu	Naval Academy	Gray (2001)
		flu	Preschool/Elementary	Neuzil (2002)
		flu	Medical school	Gerth (1987)
Measles virus	Virus	measles	Elementary	Perkins (1947)
Mumps virus	Virus	mumps	Medical school	Gerth (1987)
Mycobacterium tuberculosis	Bacteria	TB	Elementary	Watson (2001)
		TB	High school	Kim (2001)

Table 18.2 (continued)

Agent	Type	Disease	Type of school	Reference
Mycoplasma pneumoniae	Bacteria	pneumonia	College	Jackson (2000)
		URI	Medical school	Gerth (1987)
		URI	Naval Academy	Gray (2001)
		URI	Preschool/Elementary	Bosnak (2002)
Neisseria menigitidis	Bacteria	meningitis	University dormitory	Round (2001)
Parainfluenza	Virus	URI	Medical school	Gerth (1987)
		URI	Nursery school	Zilisteanu (1966)
Respiratory Syncytial Virus	Virus	RSV	College	Jackson (2000)
		RSV	Medical school	Gerth (1987)
Rhinovirus	Virus	colds	Nursery school	Beem (1969)
Streptococcus pneumoniae	Bacteria	URI	Naval Academy	Gray (2001)
Streptococcus pyogenes	Bacteria	URI	College	McMillan (1993)
		Rheumatic fever	Elementary	Dierksen (2000)
		Pharyngitis	Elementary	Hoebe (2000)
		Rheumatic fever	Elementary/High school	Olivier (2000)
Varicella-zoster virus	Virus	Chickenpox	Elementary	Bahlke (1949)

museums and libraries may impact both the occupants as well as the stored materials. Most books are made from cellulose and can be degraded by a variety of microbes and insects which may include allergens and a few potential pathogens.

Over 84 microbial genera, representing 234 species, have been isolated from library materials like books, paper, parchment, feather, textiles, animal and vegetable glues, inks, wax seals, films, magnetic tapes, microfilms, photographs, papyrus, wood, and synthetic materials in books (Zyska 1997). Many of the fungi identified in library materials can produce mycotoxins and cause respiratory and other diseases. Table 18.3 summarizes the variety of microbes that have been found in libraries and museums, and indicates the type of materials that they can grow on. The term 'deteriogen' in the table refers to microbes that can cause biodeterioration of materials.

Libraries often use carpeting to quiet the noise of foot traffic, but carpets tend to accumulate fungi and bacteria over time due to the fact that they settle in air or are brought in from the outdoors on shoes and clothes. In one study of carpeted buildings, carpet dust was found to contain 85,000 cfu/gm of fungi, 12,000,000 cfu/gm of mesophilic bacteria, and 4,500 cfu/gm of thermophilic bacteria (Cole et al. 1993). Foot traffic tends to aerosolize microbes and causes them to settle in other locations, including on books and materials. Aerosolized microbes can also be inhaled, leading to allergies and asthma. Carpets have a high equilibrium moisture content that favors microbial growth (IEA 1996).

Fabrics kept in museums, especially ancient cloth, are subject to biodeterioration from fungi and bacteria. Fungi can grow extensively on cotton fibers at the right humidity and growth rates are highest on 100% cotton (Goynes et al. 1995). Studies of biodeterioration caused by fungi that grow on paintings have isolated over one hundred species of fungi, with the most common species being *Alternaria, Cladosporium, Fusarium, Aspergillus, Trichoderma*, and *Penicillium* (Inoue and Koyano 1991).

Ultraviolet light is an option for disinfecting surfaces and materials, but it can cause damage and discoloration to pigments and paint and therefore is not necessarily suitable for decontaminating books that are already damaged by microbial growth. UVGI is best used for disinfecting the air and especially for removing mold from air conditioning systems. In-duct UVGI can greatly aid in reducing airborne levels of bacteria and spores and in removing accumulated mold spores from air conditioning cooling coils, which are used extensively to control humidity in libraries and museums. Keeping cooling coils disinfected will minimize the spread of spores through a building as well as reducing energy costs (see Chap. 10). UVGI systems can be used selectively in areas of museums and libraries that do not contain sensitive materials, such as cafeterias. Lower Room UV systems may also be ideal for hallways and entryways (where no materials are stored) where outdoor spores may be tracked into buildings. For more detailed information on technologies and techniques for dealing with biocontamination of sensitive materials in libraries and museums see Kowalski (2006).

Table 18.3 Air and surface microbes in museums and libraries

Microbe	Type	Location	Hazard
Acremonium	Fungi	feathers, leather	allergen
Actinomyces	Bacteria	cotton textiles	allergen
Alternaria	Fungi	paintings, paper	allergen
Arthrinium	Fungi	library air	allergen
Arthrobacter	Bacteria	museum air, paintings, frescoes, building materials	deteriogen
Aspergillus	Fungi	paintings, feathers, leather, books, documents, textiles	allergen
Aureobacterium	Bacteria	museum air, paintings	deteriogen
Aureobasidium	Fungi	paintings, stained glass, limestone, library air	allergen
Bacillus	Bacteria	paintings, frescoes, building materials, cotton textiles	deteriogen
Chaetomium	Fungi	ancient documents, textiles	allergen
Chrysosporium	Fungi	feathers, leather	allergen
Citrobacter	Bacteria	books	deteriogen
Cladosporium	Fungi	paintings, limestone, frescoes, cotton, paper, library air	allergen
Corynebacterium	Bacteria	cotton textiles, books	pathogen
Curvularia	Fungi	cotton textiles	allergen
Cyanobacteria	Bacteria	building materials	deteriogen
Enterobacter	Bacteria	books	pathogen
Epicoccum	Fungi	library air, paper	allergen
Eurotium	Fungi	books	allergen
Exophiala	Fungi	limestone	allergen
Fusarium	Fungi	paintings, textiles, library air, paper	allergen
Geomyces	Fungi	stained glass	allergen
M. tuberculosis	Bacteria	books	pathogen
Microbacterium	Bacteria	museum air, paintings	deteriogen
Micrococcus	Bacteria	museum air, paintings, cotton textiles	deteriogen
Micromonospora	Bacteria	cotton textiles	allergen
Mucor	Fungi	cotton textiles	allergen
Paecilomyces	Fungi	limestone, cotton textiles, library air	allergen
Paenibacillus	Bacteria	books	deteriogen
Penicillium	Fungi	paintings, feathers, leather, documents, limestone, textiles	allergen
Phialaphora	Fungi	frescoes, building materials	deteriogen
Phoma	Fungi	limestone, cotton textiles	allergen
Pithomyces	Fungi	library air, paper	allergen
Proteus vulgaris	Bacteria	paintings	deteriogen
Rhizopus	Fungi	paintings, textiles	allergen
Rhodotorula	Fungi	stained glass	allergen
Smallpox	Bacteria	books	pathogen
Stachybotrys	Fungi	textiles	allergen
Staphylococcus	Bacteria	books	pathogen
Streptococcus	Bacteria	books	pathogen
Streptomyces	Bacteria	frescoes, building materials	deteriogen

Table 18.3 (continued)

Microbe	Type	Location	Hazard
Trichoderma	Fungi	paintings, limestone, textiles, paper, library air	allergen
Tritirachium	Fungi	frescoes, building materials, library air	deteriogen
Ulocladium	Fungi	paintings	allergen
Ustilago	Fungi	stained glass	allergen
Verticillium	Fungi	stained glass, limestone, frescoes	deteriogen

18.7 Agricultural and Animal Facilities

Agricultural facilities pose a variety of occupational microbial hazards including infectious diseases from farm animals, allergies from animal dander and foodstuffs, and health threats from mold spores or actinomycetes. Animal facilities like barns, poultry houses, swine houses, and kennels can have the highest levels of bioaerosols seen in any indoor environments. Animal facilities may also include non-agricultural buildings used to house or service animals such as pet shelters and zoos. Many animal pathogens can transmit to humans by direct contact or by the airborne route. The microorganisms of greatest concern are those that can become airborne in animal facilities and these are often respiratory pathogens and allergens. Allergens can be produced as a byproduct of animal husbanding or from animal waste, animal feeds, or other farm produce. The actinomycetes are particularly common type of bacteria found in agriculture and can grow on moldy hay. Farmers may be routinely exposed to very high concentrations of actinomycetes and may inhale as many as 750,000 spores per minute (Lacey and Crook 1988). Farmer's Lung represents a group of respiratory problems that often afflict farm workers who receive chronic exposure to high concentrations of actinomycetes (Pepys et al. 1963).

Table 18.4 lists some of the most common microorganisms that occur in animal and agricultural environments, and that can transmit to man by various routes. The diseases caused and natural source are identified. For information on the UV susceptibility of these microbes see Appendices A, B, and C. Most of these microbes can transmit by direct contact or by the airborne. Table 18.5 provides a list of microbes found in sewage, many of which can become airborne.

Natural ventilation is common in agricultural facilities but mechanical ventilation will generally provide superior control of airborne microorganisms. However, filtration is often necessary to clean both outdoor air and indoor recirculated air. Recirculated air in animal facilities can be cleaned more effectively through the use of UVGI combined with filtration, and this approach works well for viruses, which may not filter out easily.

Other applications for UVGI in animal facilities include Upper Room systems, and area disinfection systems. After-hours UV disinfection systems are also appropriate for animal facilities provide the animals can be periodically removed from

Table 18.4 Common agricultural and animal pathogens and allergens

Microbe	Type	Disease or infection	Natural source
Acinetobacter	Bacteria	opportunistic/septic infections,	Environmental, soil, sewage
Actinomyces israelii	Bacteria	actinomycosis	Humans, cattle
Aeromonas	Bacteria	Non-respiratory opportunistic infections, gastroenteritis	Environmental, water, soil
Alcaligenes	Bacteria	opportunistic infections	Humans, soil, water,
Alternaria alternata	Fungi	allergic alveolitis, rhinitis, irritation, asthma, toxic	Environmental, indoor growth on paint, dust
Aspergillus	Fungi	aspergillosis, alveolitis, asthma, allergic fungal sinusitis, ODTS, toxic	Environmental, indoor growth on insulation and coils.
Bacillus anthracis	Bacteria	anthrax, woolsorter's disease	Cattle, sheep, other animals,
Brucella	Bacteria	Brucellosis, undulant fever	Goats, cattle, swine, dogs, sheep, caribou, elk, coyotes, camels.
Chlamydia psittaci	Bacteria	Psittacosis	Birds
Cladosporium	Fungi	chromoblastomycosis, allergic reactions, rhinitis, asthma	Environmental, indoor growth on dust,
Clostridium	Bacteria	tetanus, gas gangrene, toxic	Sheep, cattle
Corynebacteria	Bacteria	diphtheria	Rabbits, guinea pigs
Coxiella burnetii	Bacteria	Q fever	Cattle, sheep, goats.
Cryptostroma corticale	Fungi	alveolitis, asthma, maple bark pneumonitis, maple bark	Environmental, found on maple and sycamore bark.
Dander, hair	Allergen	cows, horses, farm animals	Agricultural
Foot and Mouth Disease	Virus	Foot and mouth disease (FMD)	Cattle
Hantavirus	Virus	Hanta virus	Rodents
Influenza A virus	Virus	flu, secondary pneumonia	Humans, birds, pigs,

Table 18.4 (continued)

Microbe	Type	Disease or infection	Natural source
Leptospira	Bacteria	jaundice	Dogs, rats
Lymphocytic choriomeningitis	Virus	LCM, lymphocytic meningitis	House mouse, swine, dogs, hamsters, guinea pigs.
Micromonospora faeni	Bacteria	Farmers Lung, pulmonary fibrosis, allergic reactions, UR irritation	Agricultural, moldy hay, indoor growth
Mucor	Fungi	allergen	dairy products
Mycobacterium kansasii	Bacteria	cavitary pulmonary disease	Water, cattle, swine
Pasteurella tularensis	Bacteria	Bubonic, pneumonic,	Rodents, rabbits, birds
Penicillium	Fungi	alveolitis, rhinitis, asthma, allergic reactions, irritation, ODTS, toxic reactions, VOCs	Environmental, indoor growth on paint, filters, coils, and humidifiers.
Rabies virus	Virus	Rabies	Dogs
Rhizopus	Fungi	allergen	Agricultural
Rickettsia	Bacteria	Epidemic typhus	Rodents, ticks
Saccharopolyspora rectivirgula	Bacteria	Farmers Lung, alveolitis,	Agricultural
Salmonella	Bacteria	Poultry, eggs	Agricultural
Sporothrix schenckii	Fungi	sporotrichosis, rose gardeners	Environmental, plant material.
Staphylococcus aureus	Bacteria	staphylococcal pneumonia	Humans, sewage
Thermoactinomyces sacchari	Bacteria	bagassosis, alveolitis, HP	Agricultural, bagasse
Thermoactinomyces vulgaris	Bacteria	Farmers Lung, pulmonary fibrosis, allergic reactions, asthma, HP	Agricultural, indoor growth in air conditioners
Thermomonospora viridis	Bacteria	Farmers Lung, HP	Agricultural
Vaccinia virus	Virus	cowpox	Agricultural
Vesicular Stomatitis Virus	Virus	VSV	Cattle, pigs, horses

Table 18.5 Microbes that may grow or occur in sewage

Microbe	Type	Group
Acinetobacter	Bacteria	Pathogen
Adenovirus	Virus	Pathogen
Aeromonas	Bacteria	Pathogen
Alcaligenes	Bacteria	Pathogen
Alternaria	Fungi	Allergen
Aspergillus	Fungi	Allergen
Bacillus anthracis	Bacteria	Pathogen
Brucella spp.	Bacteria	Pathogen
Calicivirus	Virus	Pathogen
Campylobacter spp.	Bacteria	Pathogen
Candida spp.	Bacteria	Pathogen
Cladosporium	Fungi	Allergen
Clostridium botulinum	Bacteria	Pathogen
Clostridium perfringens	Bacteria	Pathogen
Corynebacterium spp.	Bacteria	Pathogen
Coxsackievirus	Virus	Pathogen
Cryptococcus neoformans	Bacteria	Pathogen
Cryptosporidium	Protozoa	Pathogen
E. coli	Bacteria	Pathogen
Echovirus	Virus	Pathogen
Enterobacter	Bacteria	Pathogen
Exophiala	Fungi	Allergen
Fusarium	Fungi	Allergen
Giardia lamblia	Protozoa	Protozoa
Hepatitis A	Virus	Pathogen
Hepatitis B	Virus	Pathogen
Hepatitis E	Virus	Pathogen
Klebsiella spp.	Bacteria	Pathogen
Listeria monocytogenes	Bacteria	Pathogen
Mucor	Fungi	Allergen
Mycobacterium	Bacteria	Pathogen
Nocardia	Bacteria	Pathogen
Norwalk virus	Virus	Pathogen
Parvovirus	Virus	Pathogen
Penicillium	Fungi	Allergen
Phialaphora	Fungi	Allergen
Poliovirus	Virus	Pathogen
Pseudomonas aeruginosa	Bacteria	Pathogen
Rotavirus	Virus	Pathogen
Reovirus	Virus	Pathogen
Rhizopus	Fungi	Allergen
Salmonella	Bacteria	Pathogen
Serratia	Bacteria	Pathogen
Shigella spp.	Bacteria	Pathogen
Staphylococcus spp.	Bacteria	Pathogen
Streptococcus faecalis	Bacteria	Pathogen
Thermoactinomyces spp.	Bacteria	Pathogen

the indoor areas in order to disinfect them. Such an approach can be more economical than scrubbing with disinfectants, and can enhance the effectiveness of manual scrubbing procedures. For more detailed information on dealing with the complex bioaerosol and dust problems in agricultural and animal facilities see Kowalski (2006).

18.8 Malls, Airports, and Places of Assembly

Facilities like malls and airports are characterized by large enclosed volumes where large crowds may be concentrated and where heavy cyclical occupancy may occur. Places of Assembly may include auditoriums, stadiums, theaters, gymnasiums, natatoriums, arenas, town halls, churches, cathedrals, temples, mosques, industrial halls, convention centers, atriums, shopping centers, and other places where large public gatherings may occur indoors. In such buildings infectious diseases may be exchanged by direct contact, indirect contact, or via inhalation, and large numbers of people may be exposed simultaneously. The large volumes of air enclosed in such facilities often ensure good mixing of air, even in naturally ventilated stadiums, and as a result the air quality is often acceptable. However, it is difficult to provide ventilation to all corners and therefore the actual airflow distribution is often uncertain.

One of the most famous outbreaks of a respiratory disease in a heavily occupied building was the eponymous Legionnaire's Disease outbreak at a convention in Philadelphia in 1976 that resulted in 29 deaths (Spengler et al. 2001). It was traced to *Legionella* contamination in a cooling tower that apparently wafted from outdoors into a crowded hallway through open doors. An outbreak of measles occurred inside a domed stadium in the Minneapolis-St. Paul metropolitan area during July 1991 that resulted in sixteen associated cases of measles in seven states (Ehresmann et al. 1995). Several tuberculosis outbreaks have occurred in churches and mosques due to a single infectious person. Dutt et al. (1995) reports one outbreak of TB in a church where one man exposed 42% of his congregation. A norovirus outbreak at a concert hall was reviewed by Evans et al. (2002) in which a concert attendee who vomited in the auditorium and a toilet. Gastrointestinal illness occurred among members of school children who attended the following day. Transmission was most likely through direct contact with contaminated fomites that remained in the toilet area.

Large facilities that use 100% outside air provide little or no opportunity for the use of UV systems, since outside air is generally clean and free of airborne pathogens, but facilities that recirculate air may benefit from in-duct UV air disinfection systems. Large facilities often have high ceilings and this provides an opportunity to use Upper Room systems for air disinfection, especially in cases where natural ventilation is employed and there is no other means for disinfecting the air. High power UV systems can be safely used in such applications since the UV lamps can be located far from the occupied floor areas. The use of UV area disinfection systems in public toilets is an appropriate means of dealing with potential fomites, or infectious particles left on surfaces.

18.9 Aircraft and Transportation

Aircraft, trains, cars, and other compact enclosed environments can pose microbiological hazards from extended exposure due to the fact that risks due to proximity are increased regardless of whether the pathogen transmits through the air or by direct contact. Large cruise ships may resemble hotels and apartment buildings in terms of their ventilation systems and health risks but smaller craft like cars and planes create extended opportunities for infectious exchanges due to the close quarters, shared breathing air, potentially extended periods of occupancy, and the limited amount of outside air that may be brought in, especially in cold climates. Other microenvironments like elevators and city buses are unlikely to play a major role in the spread of contagious diseases due to their brief occupancy times.

Aircraft are one of the most crowded environments in which people remain for extended periods of time and the potential for airborne disease transmission is fairly obvious, except perhaps to airline owners who fly in private jets. Airplanes are potential vectors for the transmission of airborne diseases between continents and play a role in the global dissemination of epidemic diseases (Masterson and Green 1991). Airline crews and passengers have a higher risk of contracting infections on long flights (NRC 2002, Ungs and Sangal 1990). Respiratory pathogens that have been identified onboard airlines include Adenovirus, Chickenpox, Coronavirus, Influenza, Measles, Mumps, *Mycobacterium tuberculosis, Neisseria meningitidis*, and SARS virus (Kowalski 2006).

It has been reported that 85% of newer airplanes have HEPA filters (GAO 2004). However, there is a common practice in the industry of referring to MERV 14 filters (95% DSP filters) as 'HEPA-like' or 'HEPA type' filters, which is misleading. MERV 14 filters, while being excellent filters for controlling spores and most bacteria, cannot guarantee protection against viruses and smaller bacteria. Coupling a MERV 14 filter with a UVGI system can, however, can provide superior performance (Kowalski and Bahnfleth 2002). Furthermore, the energy costs associated with using HEPA filters may not be justified when a simple combination of a MERV 13–15 filter and an URV 13–15 UVGI system will provide comparable results at lower cost. UVGI systems can be installed in the recirculation ducts of airplanes as well as being located at individual seats (in the overhead 'gaspers').

The transmission of infectious disease aboard ships is a recurring phenomenon, with onboard transmission of some diseases such as Norwalk virus and Legionnaire's Disease being favored. The incidence of respiratory disease aboard military ships increases as ship size decreases (Blood and Griffith 1990). A study of a tuberculosis outbreak aboard a Navy ship found that although proximity and direct contact played a role in transmission, airborne transmission of droplet nuclei, including via the ventilation system, was responsible for most of the secondary infections (Kundsin 1980). It is common for outbreaks aboard ships to consist of multiple viral and bacterial infections, including diarrheal illness and influenza (Ruben and Ehreth 2002). Noroviruses are responsible for 23 million cases of illness each year and Norwalk viruses have recently caused numerous outbreaks of gastroenteritis on cruise ships. They are largely attributed to fomites on ship surfaces.

During 2002, cruise ships with foreign itineraries sailing into US ports reported 21 gastroenteritis outbreaks on 17 cruise ships, of which most were identified as noroviruses (Cramer et al. 2003). In an influenza outbreak aboard a cruise ship from Hong Kong in 1987, 38% of passengers came down with acute respiratory illnesses (Berlingberg et al. 1988).

UV applications for ships include in-duct UV systems to interdict recirculated pathogens and allergens, and surface irradiation systems to control fomites. Noroviruses may be particularly susceptible to After Hours UV systems placed in hallways, bathrooms, and other locations where occupancy is intermittent. Cruise ships can also be irradiated and decontaminated between voyages by portable UV systems.

18.10 Sewage and Waste Facilities

Most of the microorganisms associated with waste are either water borne or food borne pathogens and allergens and workers in sewage, wastewater, and waste processing industries are subject to occupational hazards from these microbes. Airborne hazards also exist since aerosolization of microbial pathogens, endotoxins, and allergens is an inevitable consequence of the generation and handling of waste material. Table 18.4 lists the most common microorganisms that have been found to grow or to occur in sewage and waste (Kowalski 2006). Many of these are human pathogens and they include bacteria, viruses, fungi, and protozoa. For information on the UV susceptibility of these pathogens refer to Appendix A, which addresses most of these species. Many of these species are potentially airborne and can cause respiratory infections, while most of the remainder are either waterborne or foodborne stomach pathogens.

Wastewater treatment workers are exposed to a variety of infectious agents and Khuder et al. (1998) examined the prevalence of infectious diseases and associated symptoms in wastewater treatment workers over a 12-month period. The wastewater workers exhibited a significantly higher prevalence of gastroenteritis, gastrointestinal symptoms, and headaches over those in a control group but no significant differences were found with regard to respiratory and other symptoms. Thorn et al. (2002), however, found that sewage workers had significantly increased risks for respiratory symptoms, including chronic bronchitis, and toxic pneumonitis, as well as central nervous system problems, over workers in non-sewage industries.

Reduction of microbial hazards in the sewage and waste industries is probably best approached using source control methods, but there are potential applications for UVGI. In-duct air disinfection can promote healthier breathing air for workers inside plants and both Upper Room and Lower Room UVGI systems can provide disinfection of both air and surfaces where mold and bacteria may accumulate. Area disinfection systems, like After-hours UV systems, may also provide a means of decontaminating areas during periods when they are not occupied (i.e. overnight).

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