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An Overview of Indoor Air Quality

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AN OVERVIEW OF INDOOR AIR QUALITY

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This thesis is designed to introduce beginning and experienced heating, ventilation and air conditioning (HVAC) engineers to common indoor air quality (IAQ) problems and solutions. The bulk of the work is a literature review of common pollutants, pollutant sources, HVAC equipment and systems, and remediation techniques. Pollutants covered include fungi, bacteria, dust mites, viruses, biofilms, microbiological volatile organic compounds (MVOC's), volatile organic compounds (VOC's), carbon dioxide, ozone, and radon. The HVAC systems covered are ventilation, direct expansion (DX), desiccant dehumidification, and system filters. The remediation techniques discussed are proper hygiene and maintenance, increased ventilation, humidity control, and proper selection of building materials.

DEDICATION

I would like to dedicate this research to the memory of my mother, Betty Marlene Wall Yontz (October 23, 1947 – July 6, 2000), and to my father, Raymond Lee Yontz for the support they have given while I have been in college.

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NOMENCLATURE

Symbol	Definition
Q	volumetric flow rate per person
C_a	ambient (outdoor) carbon dioxide concentration
C_{max}	maximum allowable carbon dioxide concentration

CHAPTER I

INTRODUCTION

This chapter serves as an introduction to indoor air quality, its history, and its terminology. A general discussion of the distinctions between indoor environmental quality and indoor air quality is meant to help the newcomer determine which factors need to be addressed in each case. Continuing in this trend, several definitions not defined elsewhere are addressed. Succeeding the definitions is a brief overview of the history from the early 1800's until the present of indoor air quality understanding and ventilation standards.

1.1 Indoor Environmental Quality and Indoor Air Quality

Indoor environmental quality (IEQ) is best defined as the quantification of the indoor environment and is defined subjectively by most people. IEQ studies focus on several different variables that may affect a person's perception of the indoor environment. These variables include temperature, humidity, lighting, interior design, and layout (Berlin, 2001). Indoor air quality (IAQ), on the other hand, is a quantification of the variables that affect the air supply only. These variables are most often the temperature, humidity, ventilation rate, material emissions, and biological emissions (Berlin, 2001). While good IAQ is often hard to define, poor IAQ is readily defined. Poor IAQ describes commercial and residential indoor spaces where occupants complain of health problems that diminish upon leaving the building (Bright et al., 1992). A building with a high frequency of IAQ complaints is said to have sick building syndrome (SBS). IAQ can be considered a subsection of IEQ; however, IAQ should be considered the most substantial determinant of IEQ. Many people claim that temperature and humidity should be considered IAQ variables. However, if the temperature and humidity ranges are such that material and biological emissions are unchanged, they are variables of IEQ only.

To illustrate the author's view on IAQ and IEQ, consider two molds growing on the ceiling of a room. Both molds grow at an equal rate and neither has been deterred after being washed by cleaning agents and repainting. One mold, call it Mold 1, releases no gases and its spores have no adverse affect on the occupants; it is just an eyesore. The other, Mold 2, produces obnoxious odors and its spores have caused several health problems for the occupants. Which one is an IAQ variable? Which is and IEQ variable? While each person may classify these molds differently, this author contends that Mold 1 is considered only during IEQ investigations since it has no adverse affect on the air quality. Mold 2 is considered an IAQ variable since it produces chemical and biological pollutants that become part the air supply; furthermore, since IAQ is a subset of IEQ Mold 2 is also considered a factor in determining the IEQ of the space as well, not to mention, it is still an eyesore.

1.2 Definitions

While most of the terminology is defined as needed within the text, several key heating, ventilation, and air conditioning (HVAC) terms need to be defined beforehand. Ventilation rate refers to the volumetric measure of outside air being introduced to an indoor space and is usually given in units of cubic feet per minute (CFM) or cubic meters per minute (m^3/min). Air exchange (or change) rate, which has units of air changes per hour (ACH), is defined as the ventilation rate per indoor volume. Air exchange rates are usually less than 0.5 ACH with 0.35 ACH being the most common. Remediation and mitigation are defined as the cleaning, removal, or repair of damage caused by indoor pollutants and are most often associated with, but not limited to, microbial growth.

1.3 A Brief History of Indoor Air Quality and Ventilation Standards

One of the oldest *clichés*, "History repeats itself," is true in both ventilation standards and ventilation systems. In ventilation systems, some of the more interesting schemes making a comeback are passive ventilation systems (most notable are the passive stack ventilation systems, see Section 3.2.2). A brief overview of IAQ and ventilation standards, condensed from Addington (2000), follows.

Throughout history, man has had some concept of "good" air and "bad" air. In the ancient world, marshlands were known to have "bad" air and were unsuited for cities. In the mid-17th Century, the definition of "bad" air was extended to include air polluted by early industrial processes. Furthermore, most wealthy people completely sealed their dwellings, which led many to die of carbon monoxide poisoning (asphyxiation). During this time, the poor burned dirty fuels (such as dung, sawdust, and softwood) for cooking and heat, this practice is still common in poorer countries today.

Perhaps the first real innovations in IAQ and ventilation were developed during the 19th Century when both the British Parliament and the U. S. Congress were trying to improve the air quality in their respective buildings. Both British and American "experts" specified ventilation rates that equipment of that day could not provide. In 1824, Thomas Tredgold recommended a ventilation rate of 4 CFM per person. Early ventilation systems, which met Tredgold's recommendation, were based on the then understanding of convective currents. These early systems relied on using heat sources, either candles or oil-burning lamps, placed within the ducts and indoor space to drive the air out of buildings. An innovation brought about by John Shaw Billings, during his tenure as Deputy Surgeon General of the Army, was the combination of the heating and ventilation systems. Instead of using a combustion source for heating the convective ventilation system, he used steam coils in ventilation shafts while heating the occupied spaces with steam radiators. In 1893, Billings recommended of 30 CFM per person. At the time, mechanical ventilation was the only system capable of handling such large amounts of fresh air. Early mechanical ventilation systems required steam engines to drive the ventilation fans. Since a system of this nature was quite massive and expensive, it was only economical for use in large, public buildings, although many mechanical ventilation systems were found in the homes of the wealthy.

CHAPTER II

INDOOR AIR POLLUTANTS

The most logical beginning for a discussion on indoor air quality is with the pollutants. Indoor air pollutants fall into two categories – microbiological agents and chemical agents. Microbiological agents include bacteria, fungi, viruses, dust mites, and their metabolic by-products. While other biological sources, such as pets and household plants, may contribute to poor indoor air quality, their effects are not a part of this study. Chemical agents consist of anything that is not generated by a biological source.

2.1 Microbiological Agents

There are two different classes of microorganisms – aerobic and anaerobic. Aerobic microorganisms are those that, like humans and animals, require oxygen. Aerobic microorganisms are found in both indoor and outdoor environments. Anaerobic microorganisms do not require oxygen and could die if left in an oxygen-rich environment. Anaerobic microorganisms are commonly found in petroleum and natural gas deposits. In general, all microorganisms have two basic requirements, a source of nutrients and an environment favorable for growth. There are five main categories of microorganisms: fungi, bacteria, viruses, mites, and biofilms (which can be a collection of the first four).

2.1.1 Fungi

A commonly found microorganism, known to exist in damp areas both indoors and out, fungi reduce IAQ by the emission of fungal spores, fungal colony fragmentation, and metabolic byproducts (microbial volatile organic compounds or MVOC's). *Aspergillus, Cladosporium,* and *Penicillium*, which are responsible for a variety of symptoms ranging from ear and eye infections to more serious effects such as asthma (Seltzer, 1995), are representative of the fungal species found indoors. Respiratory ailments have been attributed to the mycotoxins contained within fungal spores. Fungal spore diameter can ranges from 3 to 30 microns (Baughman and Arens, 1996).

Fungi require water, carbon, and nitrogen. The amount of nitrogen to which fungi are exposed cannot be limited since air is about 70% nitrogen. Water and carbon sources, however, can be minimized. A source of carbon is an important factor related to fungal growth and spore emissions. If carbon is plentiful, a fungi colony will grow at a significant rate and spore emissions will increase. Common carbon sources within buildings include dust buildup, soap scum, dead skin, textiles, wood, and adhesives (such as those found on wallpaper and other laminated surfaces). Since fungi acquire most nutrients in the form of solution, the availability of water on the surface is necessary for fungal growth.

Fungi by nature are very hardy microorganisms. The temperature range in which they can grow is fairly large, and the range in which they can survive is even larger. The preferred temperature range for fungal growth is 32 – 104 °F (0 – 50 °C) according to Baughman and Arens (1996). When the temperature is above this range, fungi will eventually die; however, the time required depends on the species and the temperature.

Below this range, fungi have the tendency to go into stasis, a state in which they neither grow nor emit spores. Since the temperature in most buildings is maintained between 65 and 75 °F (18 and 24 °C), building interiors are an ideal environment for fungal growth.

Since fungi require liquid water, relative humidity is not a significant factor. For instance, fungi have been known to grow with relative humidity as low as 15 %. In nature, fungi are found growing on decaying plant and animal material, which trap large amounts of moisture. Fungi can also grow in water; however, their growth rates are usually greatly reduced. In buildings and building systems, fungi are typically found in bathrooms, kitchens, near cooling coils, and in the cooling water. One study found that fungi counts in condensate drain pans, which are located under the cooling coils, were about 200,000/mL (Morey et al., 1986).

2.1.2 Bacteria

Bacteria, like fungi, prefer moist environments; however, bacteria prefer warmer environments. Unlike fungi, bacteria live within human and animal hosts as well as outside the hosts. When found outside of a host, bacteria are strongly affected by relative humidity. Common locations for bacteria within buildings include kitchens, bathrooms, HVAC equipment (especially cooling coils), sewage and drainage pipes, and certain types of humidifiers. Bacteria, in the form of biofilms (see below), are believed to be the leading causes of many recurring illnesses. *Legionella pneumophila*, the cause of Legionnaire's disease, and *Escherichia coli* (*E. coli*) are well known of bacteria.

The effects of temperature and relative humidity on general bacteria growth vary with the strain of bacteria. According to Seltzer (1995), the temperature range for many kinds of bacteria is 77 – 122+ °F (25 – 50+ °C). A study done by Donathan and Osborne (1994) reported that general bacterial growth rates in evaporative cooling water increased as the temperature was increased from 65 °F to 95 °F (18 °C to 35 °C). Seltzer (1995) found an indoor relative humidity range of 35 – 50 % generally minimized bacteria growth. For example, *Klebsiella pneumoniae* has minimal growth between 35 % and 85 % relative humidity.

2.1.3 Viruses

Viruses are usually found within human and animal hosts and are responsible for a wide range of diseases and other health detriments. Unlike bacteria and fungi, viruses travel only as bodies and do not emit any kind of spores or chemicals into the air. Baughman and Arens (1996) state that aerosol movement of viruses occurs through human-ejected droplets (0.5 to 5 μm in diameter), which either other human or animal hosts ingest or make contact with surfaces.

Because of their nature, viral growth outside a human or animal host is extremely limited; however, the survival of viruses does occur given the right ambient environment. A study done by Mbithi et al. (1991) showed that Hepatitis A has an affinity for both low temperature and low relative humidity and has a low survival rate in “normal” ambient air. Cox (1989) reviewed the effect of relative humidity on several viruses including the polio virus and the foot-and-mouth-disease virus. Cox showed that below 70% RH, these viruses could not generate a protective coating to handle the low relative humidity values and became too unstable to survive. Cox also showed that the opposite was true for viruses such as the influenza virus, which was unstable for high relative humidity values. While the exact nature of the difference in viral relative humidity preference is not known, Cox suggests that the structural components of the lipid layers (protective coatings) differ from one viral strain to the next with the relative humidity preference changing for different strains. Temperature, however, does not significantly affect the development of the lipid layer. For more information, see Cox (1989).

Sale (1972) discussed the physics involved in the emissions of virus and bacteria in droplets. For example, a person sneezes and emits viruses in droplets. If the air is dry, the air quickly absorbs the water in the droplet and the virus is suspended in the air. Since the virus is not very massive, convective air currents can carry it effortlessly. If the air is relatively moist, the droplet will retain most of its moisture. Since the droplet is significantly more massive than the virus, it will fall farther and be more likely to land on a surface.

2.1.4 Dust Mites

A common problem in many homes, the dust mite contributes to the aerobiology of the ambient air by emission of eggs, gland secretions, and fecal products. Platts-Mills (1989) stated that the major human side effect from dust mites is asthma due to an abundance of mite fecal matter in the ambient air. The other two mite products, eggs and gland secretions, are considered negligible in terms of allergen effects. Growth areas for mites consist of dust clouds and dusty areas within buildings, but furniture and carpeting are potential areas for mite growth as well. For temperature effects, Platts-Mills (1989) state that the common dust mite grows best in the temperature range of 60 – 80 °F (15 – 27

°C). For relative humidity effects, Seltzer (1995) contends that most dust mite species grow best when relative humidity is above 70%.

2.1.5 Biofilms

Biofilms are a complex community of microorganisms that have an increased immunity to antimicrobial agents. Biofilms may be one or several different species, and most biofilms are nonhomogeneous in both time and space. Since the vast majority (90-98%, depending on the source) of microorganisms in the world live in a biofilm, a significant portion of microbiology research is being directed towards understanding biofilms. In general, microorganisms in a biofilm state will have reduced metabolism and will excrete a polymer gel that helps to adhere the microorganisms. Due to the complex structure of biofilms, the microorganisms within biofilms often mutate to fit the changing surroundings. For example, if a biofilm consists of strictly aerobic microbes, the microorganisms farthest from the surface of the biofilm will live in an anaerobic environment; however, these microbes will not die out due to the lack of oxygen, but will adapt to the anaerobic environment. (Donlan and Consterton, 2002; Flemming, 1993).

The increased resistance of biofilms to antimicrobial agents has been the center of a lot of research in the microbiology field. Some have theorized that the reduced metabolism of biofilm microbes explains the increased immunity of the biofilm; however, De Lancey Pulcini (2001) states that the metabolism reduction is not enough to warrant the observed immunity. Others have speculated that another possibility of the increased biofilm resistance is due to a reduction in the penetration of antibodies into the biofilm. This is refuted by Stone et al. (2002), which showed that, while the antibodies penetrate biofilm colonies slower than the nonbiofilm colonies, antibodies did penetrate the biofilm completely. Anderl et al. (2000) has theorized that the polymer gel within the biofilm may change the structure of the antibodies as they flow through the biofilm; however, this has not been verified.

Some properties of the individual microorganism are retained within the biofilm. For example, bacteria that are extremely sensitive to desiccation (i.e., those that die when dehydrated) will, in a biofilm, still have the tendency to die out if desiccated; however, the desiccation rate and stresses may need to be significantly greater to ensure killing the biofilm. The antibiotics that work against the individual microorganisms will still affect the same microorganisms in biofilms, but at a reduced rate.

2.1.6 Microbial Volatile Organic Compounds (MVOC's)

Microbial volatile organic compounds, or MVOC's, are defined to be the volatile organic compounds (VOC's), usually hydrocarbons, generated by the microorganisms. Fischer et al. (1999) tested 13 fungi taken from a compost facility in Germany and determined the VOC's produced by each species. A total of 109 different VOC's were generated by the species sampled; however, several of these MVOC's were only produced by certain species. Table 2.1 contains a list of the fungi for whom characteristic MVOC's could be determined. Several of the MVOC's produced by the fungi species tested could not be clearly identified and are noted by appending "like" at the end of the VOC it closely resembled. Others could not be identified at all; however, the family of the VOC could be determined. A study conducted by Ezeonu et al. (1994) investigated the MVOC's produced by *Acremonium obclavatum* and *Aspergillus versicolor*. One of the more startling findings of this study is that both fungi species produced benzene gas, a suspected carcinogen, while colonizing a fiberglass duct liner.

Table 2.1 Selected Fungi Species and their Characteristic Volatile Organic Compounds (Fisher et al., 1999).

Fungi Species	Characteristic Volatile Organic Compounds
Aspergillus candidus	hexanoic acid ethyl ester, methoxybenzene, 3-cycloheptene-1-one, 1,3,6-octatriene
Aspergillus fumigatus	p-metha-6,8-diene-2-ol acetate, camphene, trans-β-farnesene, α-pinene, 3 unknown terpenes
Aspergillus versicolor	1-(3-methylphenyl)-ethanone, 6-methyl-2-heptanome
Emericella nidulans	2,3-dimethyl-butanoic acid methyl ester, 4,4-dimethyl-pentenoic acid methyl ester, 2-methyl-butanoic acid methyl ester, α-humulene like, α-terpinolene, three unknown terpenes
Paecilomyces variotii	δ-4-carene, megastigma-4,6(E),8(Z)-triene, neo-allo-ocimene, β-phellandrene
Penicillium crustosum	2-ethylfuran, 2-ethyl-5methylfuran, isopropylfuran
Penicillium clavigerum	β-caryophyllene
Penicillium cyclopium	2-methyl-2-bornene, germacrene A
Penicillium expansum	1-methoxy-3methylbenzene (3-methyl-anisole), aromadendrene, bicycloelemene

Table 2.2 MVOC'S Produced by *Acremonium obclavatum* and *Aspergillus versicolor* (Ezeonu et al., 1994).

Species	MVOC's Produced in Enriched Agar	MVOC's Produced in Colonized Fiberglass Insulation
Acremonium obclavatum	ethanol acetone 2-butanone methyl benzene cyclohexane benzene	cylotrisiloxane limomene arsenous acid pentane benzene
Aspergillus versicolor	1,3-dimethoxy benzene methyl benzene cyclotetrasiloxane	methyl benzene ethanol cyclotisiloxane limonene ethyl hexanol benzene

2.2 Chemical Agents

While bioaerosols constitute a major part of all indoor air contaminants, non-biological aerosols should not be discounted in terms of adverse health effects on building inhabitants. Non-biological indoor air contaminants can be described as either volatile organic compounds or other compounds. One major difference between the non-biological and the biological agents is that the non-biological agents are almost always more concentrated indoors than outdoors.

2.2.1 Volatile Organic Compounds (VOC's)

According to Carrer et al. (2000), volatile organic compounds, or VOC's, "consist of hundreds of different organic compounds," mostly hydrocarbons. VOC's have boiling points ranging from less than 32 °F (0 °C) to a maximum of 750 °F (400 °C) (Yu and Crump, 1997). Modern construction materials used within buildings have the potential to cause serious VOC problems. While biological contaminants must migrate from the outdoor environment, VOC's usually come from within the building itself. In most instances, the VOC sources are common materials used in the construction and decoration of the building and include carpet, upholstery, adhesives, manufactured lumber (such as plywood and medium density fiberboard, MDF), wallpaper, paint, and varnish. Other commonly found sources are cleaning supplies, disinfectants, and smoking tobaccos. Table 2.3 lists some common VOC sources and maximum emission rates compiled from Grimsrud and Hadlich (1999), Black (1998), and Yu and Crump (1998).

Table 2.3 Common VOC Sources and Emission Rates

VOC Source	Maximum Source Strength ($\mu g/m^2$-hr)
Waxes spread on surfaces	90,000,000.00
Solvent-based adhesives	20,000,000.00
Liquid cleaner, disinfectant	1,100,000.00
Water-based adhesives	2,000,000.00
Furniture spray polish	300,000.00
Wall and floor adhesives	271,000.00
Carpet assembly with adhesive on	153,000.00
Laser printers*	110,200.00
Carpet adhesives	99,000.00
Dry process photocopiers*	91,200.00
Floor waxes	80,000.00
Plastic sealant	72,000.00
Dry cleaned clothing	27,000.00
Silicone sealant	26,000.00
Personal computers*	24,200.00
Vinyl/PVC flooring	22,280.00
Silicone caulk	13,000.00
Wood varnish	10,000.00
Polyurethane wood finish	9,000.00
Polyurethane lacquer	6,000.00
Textile floor covering	2,000.00
Plywood paneling	1,450.00
Extruded polystyrene thermal	1,400.00
Rubber floor covering	1,400.00
Textile wall covering	1,400.00
Latex caulk	637.00
Acrylic latex paint	430.00
Neoprene/polyethylene caulk	340.00
Rubber-backed nylon carpet	300.00
Particleboard	200.00
Gypsum board	30.00
Bituminous tar vapor barriers	6.30
Extruded polyethylene duct and	0.80
Urethane sealant	0.13

* Total volatile organic compound (TVOC) rate measured in µg/hr.

Many common emitters of indoor VOC's are polymer materials used within buildings. For most polymer materials, the emission of VOC's begins at some initial concentration that diminishes over time. Some polymer materials, like alkyd paints, initially emit VOC's at significantly high rates; where as other, such as varnishes and vinyl, have relatively low initial emission rates. Chang and Guo (1998) showed that aldehyde emissions from freshly applied alkyd paints reached maximum values of over 60 parts per billion (60,000 parts per million, ppm) while the paint was drying. Emissions decreased exponentially 20+ hours after the paint had dried. However, aldehydes have a low decay rate, and the concentration of aldehydes within the space remained relatively constant although the emission rates declined. The emission rates of most volatile organic compounds have a direct relationship with changes in both relative humidity and temperature. Since the boiling ranges of VOC's cover a wide spectrum, temperature effects depend mainly on the VOC in question.

2.2.2 Ozone

Ozone is recognized by the EPA as a respiratory irritant and is produced by photochemical reactions of hydrocarbons and nitrogen oxides. The main source of ozone is either the infiltration or ventilation of high ozone concentration air from outside the building to the inside (Baughman and Arens, 1996). Other sources of ozone include dry process photocopiers, laser printers, and personal computers, which have maximum emission rates of 5.0, 4.2, and 0.02 mg/hr, respectively (Black, 1998). Average indoor ozone concentrations, range from 10% to 80% of the outdoor ozone concentrations, indicating a potential for very high ozone levels indoors if the building ventilation is not equipped activated carbon filters. According to Baughman and Arens (1996), the half-life of ozone in normal indoor environments is 6 – 12 minutes.

2.2.3 Carbon Dioxide

The main indoor emitters of carbon dioxide (CO_2) are building occupants from either simple respiration and/or smoke exhalation. Apte et al. (2000) cite literature reviews that indicate a strong correlation between high CO_2 levels indoors and the prevalence of SBS symptoms with the building occupants. According to Lugg and Batty (1999), an average of 20 % of occupants will be dissatisfied with carbon dioxide concentrations of 700 ppm higher than the outside concentration, which translates to a CO_2 concentration of 1000 ppm, assuming the ambient concentration is about 300 ppm. Furthermore, Bright et al. (1992) recommend that carbon dioxide concentrations should be maintained below 600 ppm. The British Building Services Research and Information Association (BSRIA), on the other hand, recommends that indoor CO_2 concentrations should be maintained below 800 ppm (Lugg and Batty, 1999). Apte et al. (2000) claim that the effects of carbon dioxide are independent of temperature and relative humidity.

2.2.4 Radon

Grimsrud and Hadlich (1999) state that radon is considered a major indoor air pollutant. The main health threat coming from radon is the potential to cause lung cancer. Radon is emitted mainly from decaying soils and is diffused into buildings through either ventilation systems or infiltration. Radon will travel with convective currents when infiltrating a building through cracks in the subfloor. No direct correlations between radon emission and the temperature and relative humidity seem to exist.

CHAPTER III

HEATING, VENTILATION,

AND AIR CONDITIONING SYSTEMS

Since most indoor air quality complaints can usually be linked, in one form or another, to the heating, ventilation, and air-conditioning systems, a detailed overview of the various HVAC systems that may be installed in buildings is a natural beginning of the remediation process. This chapter focuses on the design and construction of buildings and building systems in light of the possible pollutants discussed in the previous chapter. At the conclusion of the chapter is a discussion of several microbial problems that may occur within the HVAC system.

3.1 Ventilation

Ventilation is necessary to dilute and exhaust indoor pollutants such as a carbon dioxide and volatile organic compounds. Two different forms of ventilation, natural and mechanical, exist and will be discussed in this section. Natural ventilation relies either on air entering through cracks in the building envelope (infiltration) or direct ventilation due to open windows and other designed entry and exit points (passive ventilation) to introduce fresh air into a building's interior. Mechanical ventilation, on the other hand, requires the use of fans to introduce fresh air and expel stale air. Traditionally, residences have been inherently designed to make use of natural ventilation, while most office buildings utilize mechanical ventilation.

Many buildings in the United States do not have proper ventilation. The common problem associated with these methods of ventilation includes either excessive or insufficient relative humidity (depending on location and season), which leads to health and microorganism problems. In some cases, naturally-ventilated homes have been found to contain a high level of microorganisms; however, the owners did not perceive any problems since the signs of the microorganisms were hidden behind the walls of the houses (Hadlich and Grimsrud, 1999).

The absence of humidity control is a serious problem with ventilation. In warm humid climates, ventilation coupled with direct expansion cooling can create an unacceptably high relative humidity; whereas, in cool dry climates, ventilation will create an indoor relative humidity that is unacceptably low. Several studies (Green, 1985, 1982, 1974; Gelperin, 1973; and Sale 1972) have shown that humidity control during the winter months helps to alleviate respiratory illnesses in both adults and children. Since ventilation alone cannot create a suitable indoor air quality, some means of humidity control needs to be implemented with the ventilation.

Natural and mechanical ventilation are the conventional methods of controlling indoor air contaminants by diluting the contaminant concentration. According to Bright et the ventilation rate necessary can be calculated by Equation 3.1, where Q is the amount of ventilation per person, 11,500 is the average concentration of CO_2 expelled per person per

$$Q = \frac{11{,}500}{C_{\max} - C_a} \tag{3.1}$$

cfm of air breathed, C_{max} is the maximum allowable CO_2 concentration, and C_a is the ambient (outdoor) CO_2 level. Equation 3.1 can be used to calculate the amount of ventilation per person according to the maximum acceptable carbon dioxide concentration recommendations of 600 ppm (Bright et al., 1992), 800 ppm (Lugg and Batty, 1999), and 1000 ppm (ASHRAE Standard 62-1989). Assuming an ambient CO_2 concentration of 300 ppm, the resulting ventilation rates are 38.33, 23.0, and 16.43 cfm/person, respectively. Since operating a ventilation system at the maximum designed ventilation rate is not always cost justifiable, demand-controlled ventilation may be used to reduce the ventilation rate when conditions permit.

3.1.1 Demand-Controlled Ventilation

One set of ventilation strategies proposed by Schell et al. (1998) uses the measurement of indoor carbon dioxide concentrations to vary the amount of ventilation and is referred to as demand-controlled ventilation (DCV). DCV, when properly designed and installed, can help buildings such as theaters, schools, large office spaces, and other places where occupancy varies reduce their energy usage. ASHRAE Standard 62-1989, Interpretation IC 62-1989-27 governs many of the requirements for DCV. The main requirement of DCV strategies is that the lag time must stay within a specified amount that varies according to building function. Lag time is the amount of time required for the ventilation system to respond to the changes in the carbon dioxide concentration of the indoor space. A minimum amount of ventilation based upon the non-occupant indoor air pollution generated should be maintained.

The locations of the CO_2 sensors are very critical to the proper operation of a DCV system. Schell et al. (1998) recommend installing the CO_2 sensor(s) within the return air duct when "the ventilation system operates continuously and where all the zones served by the air handler have similar levels of activity and occupant densities, occurring at the same time." The use of wall-mounted sensors is recommended in all other situations where DCV may be warranted. If wall mounted sensors are used then either each space being ventilated should have its own sensor or a single sensor can be placed in the most critical space being ventilated. Three different DCV control approaches are discussed by Schell et al. (1998); a brief summary of each will be presented. The only difference between each approach is the manner in which they respond to the CO_2 concentration changes.

Set-point control is a step-response approach; in other words, the amount of ventilation is increased to the full design amount when the CO_2 concentration reaches a set value. In most situations, set-point control may not have sufficient lag times since it is possible for a partially-filled space to not trigger the ventilation system when ventilation is needed. However, in spaces where the occupancy reaches full design quickly, such as an auditorium or theater, set-point control may be able to achieve acceptable lag times. The main advantage to set-point control is the ease in which it can be implemented.

Proportional control is a linear-response approach. As the indoor CO_2 concentration increases, the ventilation rate increases at a set rate. Proportional control can be applied to a wide range of buildings and spaces. In several instances, proportional control can provide an acceptable lag time since it is more sensitive than set-point control.

Exponential control is, as the name implies, an exponential-response approach. It will behave similarly to proportional control with the exception that the ventilation rate increase is not constant. Exponential control usually utilizes either a proportional-plus-integral or a proportional-integral-derivative control algorithm. Exponential control has the least amount of lag of the three approaches allowing it to be used whenever the previous approaches do not supply an adequate lag time. On the other hand, exponential control requires significantly more advanced design and knowledge to implement. Furthermore, if the lag time is still unacceptable, then demand-controlled ventilation cannot be utilized.

Other approaches in DCV could include adding more sensors, measuring the outdoor CO_2 concentration, and/or using even more elaborate control algorithms. The monitoring of the outside CO_2 concentration could be particularly useful since ASHRAE Standard 62 recommends no ventilation if outdoor carbon dioxide concentrations are above 600 ppm. In addition to responding to carbon dioxide concentrations, DCV systems could be designed to handle other gaseous pollutants such as those caused by combustion. Hadlich and Grimsrud (1999) list carbon monoxide (CO), nitrogen monoxide (NO), and nitrogen dioxide (NO_2) as the more dangerous by-products of combustion.

3.1.2 Passive Ventilation Systems

Natural ventilation has traditionally been utilized in residential construction in both Europe and the United States, with the Europeans relying on passive ventilation while the United States has exploited infiltration. Over the last few years, however, natural ventilation has fallen out of favor due to both energy usage and the difficulty of maintaining good indoor air quality. Axley (1999) explores the use of passive stack ventilation (PSV) systems within residences. The advantage of PSV systems is that they require little or no extra energy costs when compared to mechanical ventilation systems. Additionally, the initial system costs are usually lower. While Axley provides several different examples of PSV applications, only a few will be discussed here. Passive stack ventilation operates by using two natural phenomena – buoyancy forces and wind. Each of the methods presented herein differ only by the manner in which these phenomena are manipulated.

Before discussing the PSV methods, several definitions need to be made. Figure 3.1 illustrates many of these definitions. A service room is defined to be any room that generates moisture; all other rooms are defined as habitable rooms. Direct ventilation refers to a service room. Indirect ventilation of a space is defined as either having an outdoor air intake and pass-through vents to adjacent rooms or having only pass-through vents to adjacent rooms. The stack duct should have a diameter of 5 in (125 mm) and 4 in (100 mm) for kitchens and bathrooms, respectively. Service room inlet vents (those found in kitchens and bathrooms) should have an open surface area of 6.2 in^2 (4000 mm^2). Room exhaust grills (or pass-through vents) should have an open surface area no less than the cross-sectional area of the stack duct. Stack terminal devices should be designed such that a suction pressure is maintained on the stack regardless of wind direction and prohibit rain, insect, and animal entry to the stack. Habitable room inlet vents should have an open area of 12.4 in^2 (8000 mm^2).

Traditional PSV systems require direct ventilation in kitchens and bathrooms while all other spaces near the external wall have indirect ventilation. Figure 3.2 illustrates how the buoyancy and wind forces generate airflow through a residence. In the diagram positive and negative pressures are denoted by plus and minus signs, respectively. The airflow rates within each room will vary according to the room's relation to the wind direction; therefore, several different alternatives to the traditional passive stack have been developed.

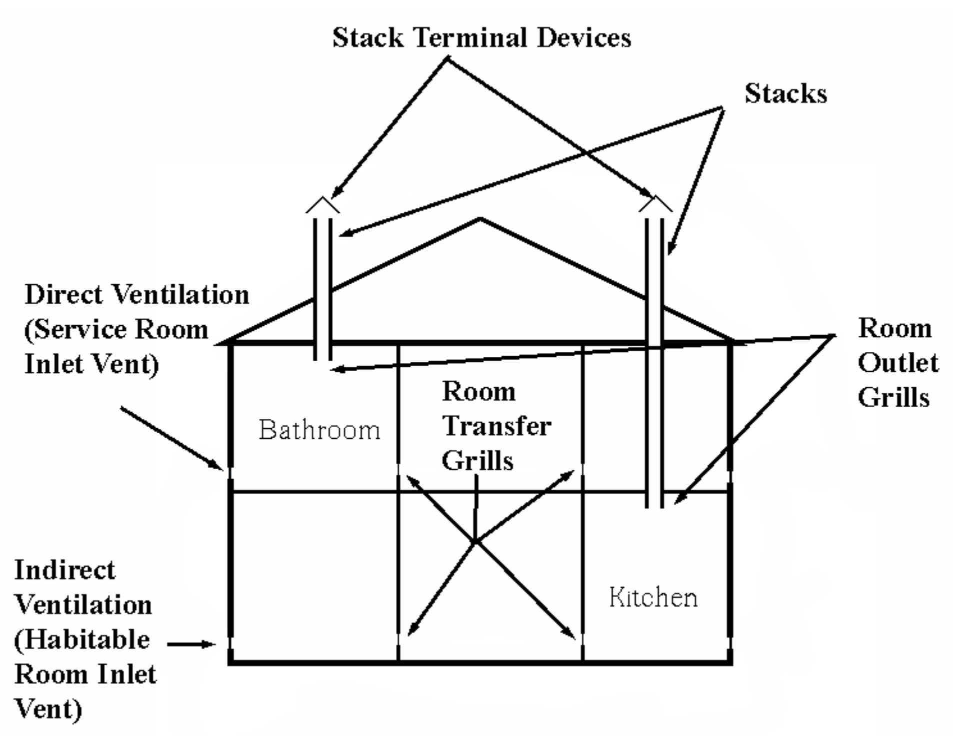

Figure 3.1 Passive Stack Ventilation Terminology

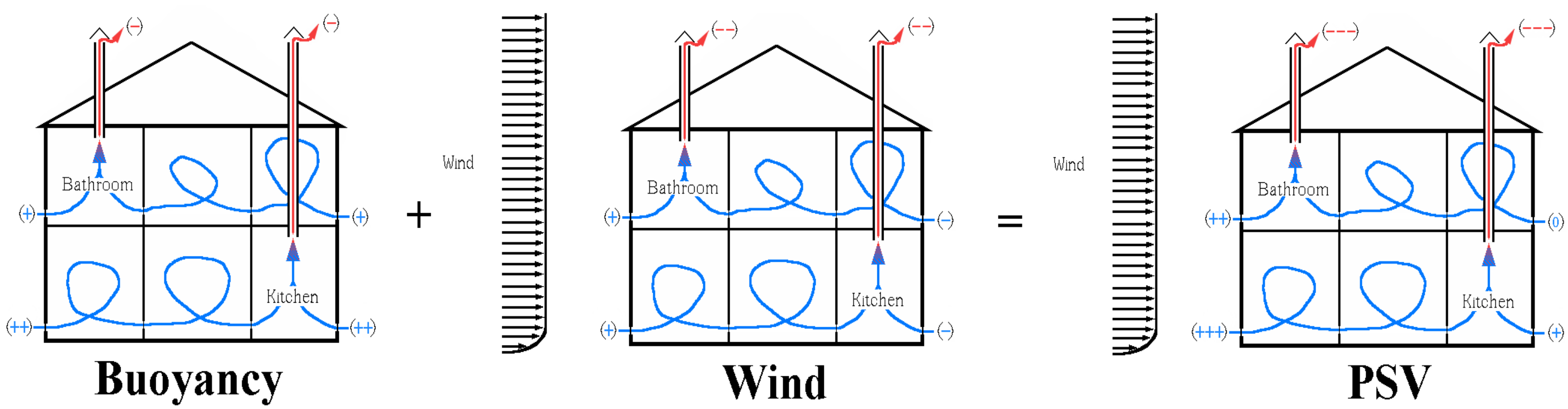

Figure 3.2 How Passive Stack Ventilation Works

One of the alternatives, shown in Figure 3.3, is a centralized PSV system with a subfloor inlet plenum. This system is designed to allow for a uniform airflow through the rooms regardless of the direction of the wind. One disadvantage is that many new residences are built with concrete slab foundations while the subfloor plenum method is more suited for conventional foundations. Furthermore, a subfloor plenum system may allow radon to enter the indoor space easier. Another alternative is the centralized balanced wind stack (BWS) system, illustrated in Figure 3.4. As with the subfloor plenum, BWS is designed for uniform airflow regardless of wind direction. Unlike the subfloor system, the BWS system can be installed in either conventional or concrete slab foundation houses. While the traditional PSV system cannot easily adjust the temperature of the ventilation air, both the subfloor and BWS systems can have heat exchangers installed to pre-treat the ventilation air.

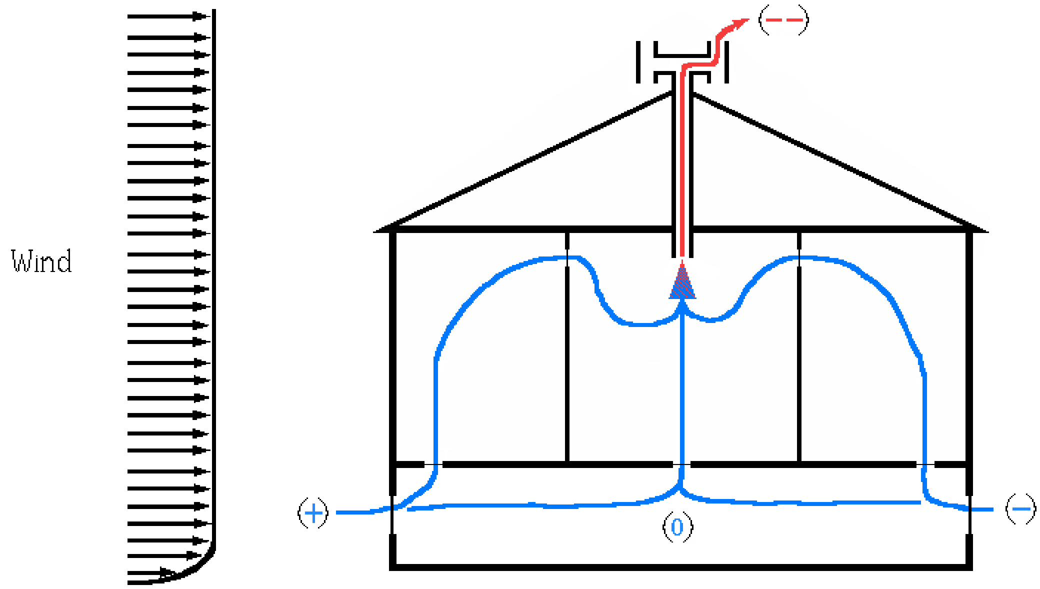

Figure 3.3 Passive Stack Ventilation with Subfloor Plenum

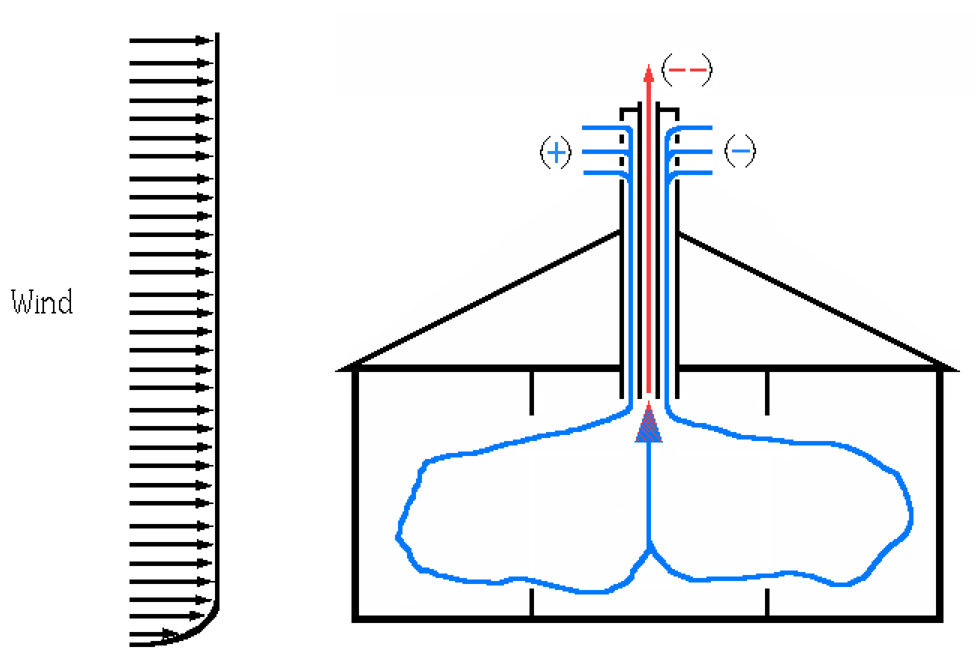

Figure 3.4 Balanced Wind Stack

3.2 Improved Filtration Methods and Technologies

Filters are best used to trap biological and inorganic particles in air rather than being used to trap moisture (Morey, 1994). Selection and placement of high-efficiency filters within a ventilation system determine how well a filter will improve the indoor air quality. ASHRAE Standard 52 dictates the testing procedure for rating filters. For further details on rating filters, refer to ASHRAE Standard 52 and Thornburg (1999).

Studies have shown that the effectiveness of filters placed in ventilation systems depends mainly on location of contaminant sources. Seltzer (1995) states that the clinical effectiveness of filters can be compromised from interior building contaminant sources such as old carpet and mattresses. Many high-efficiency filters such as HEPA, electrostatic, and precipitator filters can lose their effectiveness from such things as carpet not being vacuumed regularly. Seltzer (1995) and Brennan (2001) recommend constant attention is paid to particulate emitters such as old rugs, in order to give filters a chance to work as efficiently as possible. Kemp et al. (1995) showed that filter efficiency for various filtration units varied from as low as 60 %, to as high as 100 %. The same study demonstrated that both fungi and bacteria grew on the filters when left without maintenance. Martin (1999) and Baril (1988) suggest that HEPA filters with the ability to catch 99+ % of incoming particles, especially bacteria and viruses, are necessary for medical facilities; Ninomura and Cohen's study (1999) found that filters with 80 % efficiency would meet this suggestion. Ninomura and Cohen also state that gas-phase filters, such as activated carbon, give a higher efficiency for trapping small-particulate contaminants, but these filters may restrict airflow through the system, raising ventilation costs. Cost benefits from using filtration within buildings are investigated in full in Dorgan et al (1999).

Filter placement is another area that is particular to a given ventilation system setup. Morey et al. (1986) recommends filter placement (with 50% to 70% efficiency) before heat exchangers within an HVAC system, but further recommends filter placement after the heat exchange units as to catch contaminants that occur downstream. Martin (1999) states that every air handling system within a medical facility needs to have at least two filters, a "prefilter" (30% effective, minimum) that is placed upstream of the heat exchange and air-handling units and a final filter (90% effective, minimum) that is placed downstream of the heat exchanger and air-handler. The prefilter prevents the larger sized contaminants from clogging up the heat exchanger(s), and the final filter helps to ensure cleaner air for patients to breathe. A study done by Green (1982) showed that filter placement after steam humidifiers gave high levels of effective prevention against microbial contamination. In order to prevent microbe buildup on the filters maintenance must be preformed regularly to either clean or change the filters; Morey (1986) recommends an interval of one month.

3.3 Cooling Coil Technology

Cooling coil technology is the conventional means of temperature control and has been extended to humidity control. Coiling coil technology uses both cooling and heating coils to subcool air to remove moisture and then reheat the supply air. This form of dehumidification can be implemented using either direct expansion (DX) or chilled and hot water supplies.

A paper published by Zhang (2001) discusses the thermodynamics of using cooling coil technology to reduce the relative humidity and temperature of the building's supply air. In the example depicted in Figure 3.5, outdoor air at 92 °F mixes with return air at 72 °F to produce mixed air 73.5°F. The mixed air is cooled down to 59 °F before being reheated to the supply temperature of 68 °F. By subcooling and reheating, an excessive amount of energy is used to condition the ventilation air to supply conditions. As the air is subcooled, the moisture in the air condenses on the coils and then drips into a collection (or drain) pan. The drain pan can become a significant source of microorganism growth, especially when clogged.

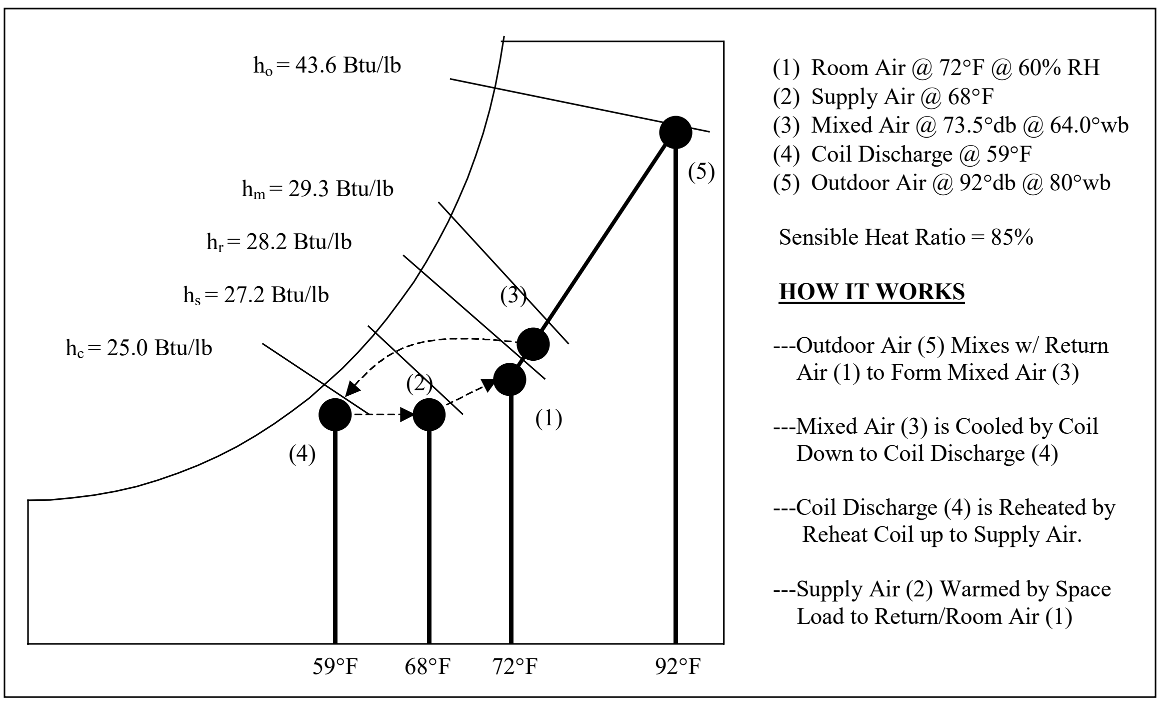

Figure 3.5 Cooling Coil Sub-Cool and Reheat Psychrometric (Zhang, 2001).

Cooling coil dehumidification has been commonly used in schools and other buildings. *Air Conditioning, Heating, and Refrigeration News* (2000) discuss IAQ improvement in schools after the installation of new air conditioners. These air conditioners were equipped with coiling coil dehumidification packages that lowered the relative humidity of the ventilation air by as much as 40 %.

3.4 Desiccant Dehumidification Units

Desiccant dehumidification units come in both solid desiccant wheel units and liquid desiccant units. The solid wheel units come in two common configurations – single-wheel units and dual-wheel units. Single-wheel units (sometimes called TWERS – Total Energy Recovery System) are commonly used in conjunction with evaporative cooling systems (which are used in several ice rinks). Dual-wheel (sometimes referred to as DWERS – Dual Wheel Energy Recovery System) and liquid units are usually paired with cooling and heating coils for temperature control. Regardless of the type, desiccant units can provide increased energy savings for ventilation. A schematic of a dual wheel desiccant unit is shown in Figure 3.6.

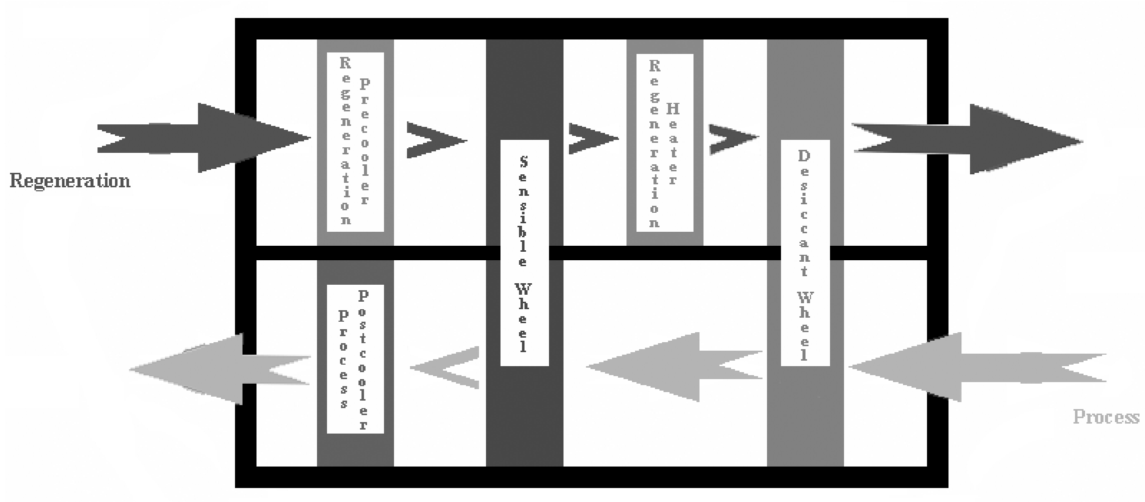

Figure 3.6 Dual Wheel Desiccant Schematic

In order to effectively discuss the benefits and disadvantages of desiccant systems, the two common methods of installation must be understood. A ventilation installation is one in which the desiccant unit is completely independent of the air-conditioning (A/C) coils. (In this paper, both the cooling and heating coils of conventional equipment are referred to as air-conditioning coils). This installation allows outdoor air to be continuously supplied to the indoor space without requiring the main air-conditioning system's fan to operate simultaneously with the desiccant unit. Another advantage to this installation is that it allows for humidity control across several control zones in a building (or a group of buildings). Common applications for ventilation installations are large office buildings and schools. A preconditioning installation is one in which the desiccant unit is connected to pretreat the outdoor air before it is treated by the main air-conditioning unit. This type of installation requires the fan on the air conditioner to operate when the desiccant unit is operating. One advantage to a preconditioning installation is that it can eliminate the seasonal variations experienced by the A/C coil, which improves the energy efficiency of the coils (Fischer, 1996). A typical range of outdoor air conditions throughout a year is shown in Figure 3.7 as the teardrop shape filled with diagonal lines. The oval in the center of the seasonal variations is the typical range of air conditions that a desiccant unit supplies nearly year-round when installed as a preconditioning system. Common applications for a preconditioning installation are homes, small commercial buildings, and retrofits.

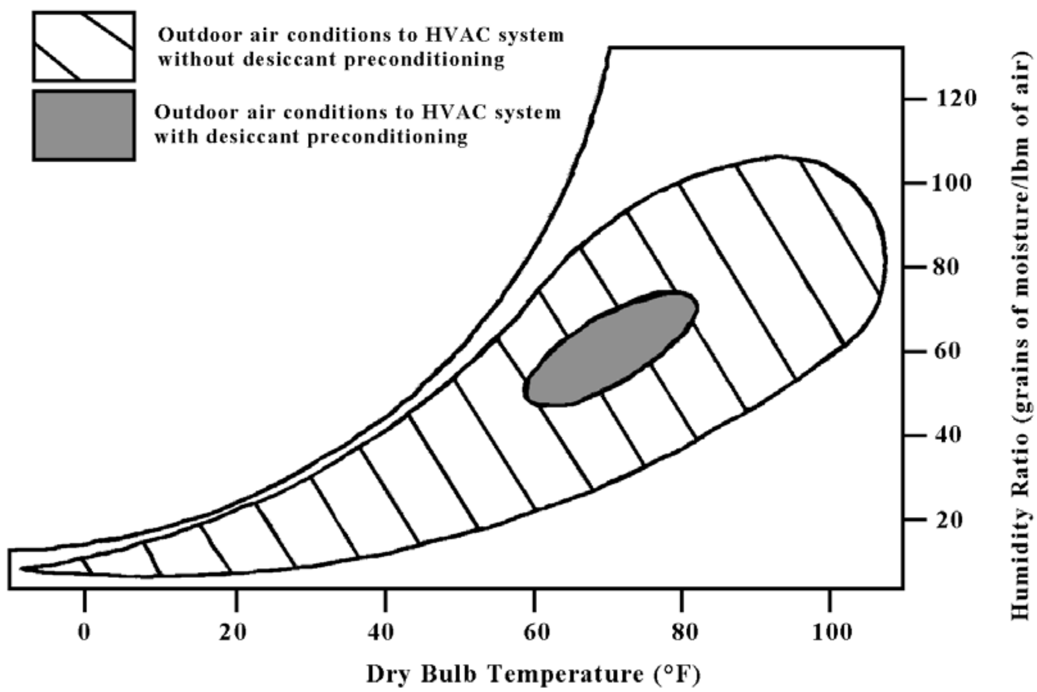

Figure 3.7 Desiccant Preconditioning.

Regardless of the type, desiccant units operate similarly. Figure 3.8 is a schematic of a desiccant system detailing both summer and winter modes of operation for a ventilation installation. The summer mode of operation for a dual-wheel unit will be discussed. For the winter mode of operation, see Fischer (1996). During the summer mode, both the heat recovery (or sensible) wheel and the desiccant wheel rotate. On the process side, warm moist air enters the desiccant wheel and is cooled and dehumidified. The air then passes through an A/C coil, for further dehumidification, before passing through the sensible wheel to be reheated without any absolute humidity change. On the regeneration side, the warm return air passes through the sensible wheel where the air is cooled without any absolute humidity change. The return air then passes through the desiccant wheel where the air is reheated and humidified before being exhausted to the atmosphere. In the example shown in Figure 3.9, the supply air is at 69 °F and 55 grains, which is both cooler and less humid than the outdoor air of 90 °F and 125 grains.

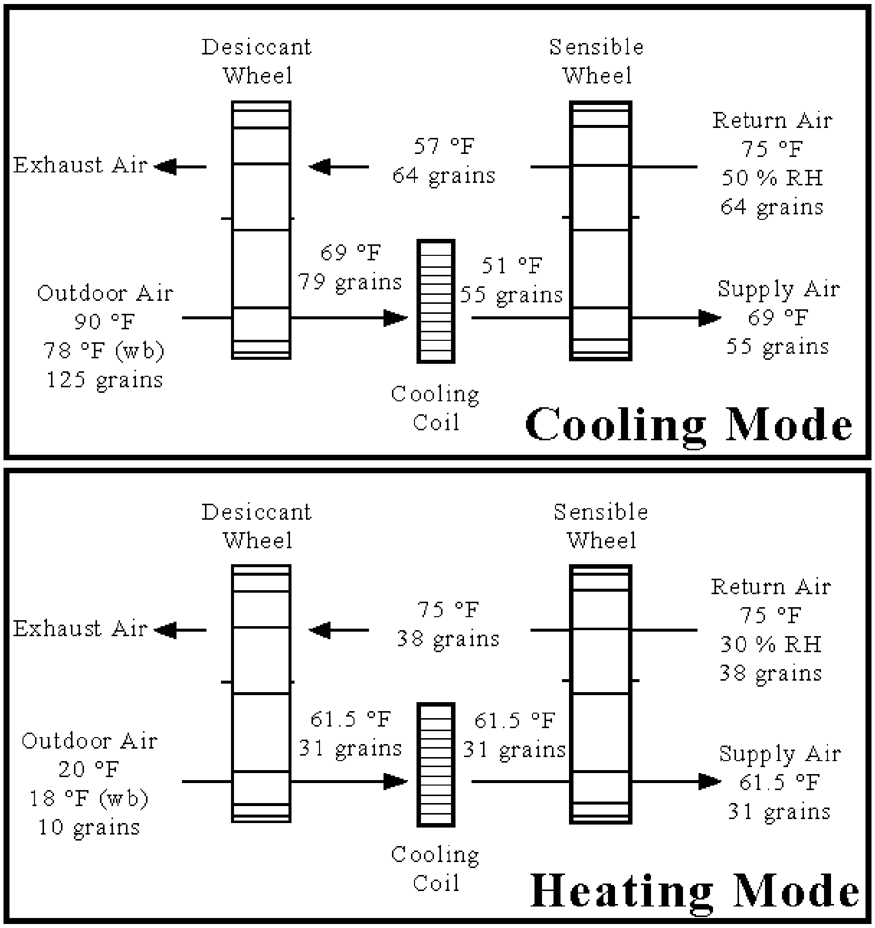

Figure 3.8 Seasonal Operation of a Dual-Wheel Desiccant Unit (Fischer, 1996).

3.5 Desiccant Dehumidification Versus Coiling Coil Dehumidification

Desiccant units have several advantages over direct expansion units. Downing and Bayer (1993) conducted an investigation into a Georgia school with indoor air quality problems. The IAQ problems at the school were so bad that students walked out of class in protest and lawsuits were filed against the school system. As part of this investigation, data of A/C coils supplying 5 cfm/person continuously, A/C coils supplying 5 cfm/person intermittently, and a dual-wheel desiccant unit supplying 15 cfm/person continuously were gathered. As Figure 3.9 shows, the A/C coils could not maintain the indoor relative humidity low enough to prevent microbial problems from developing; however, the dual-wheel desiccant unit was able to maintain the humidity level low enough to help prevent microbial problems. At 5 cfm/person intermittently, the direct expansion unit operates below the maximum recommended relative humidity during the occupied hours. During the unoccupied hours, when the units are not run, the relative humidity rises above the threshold. At 5 cfm/person continuously, the direct expansion unit cannot maintain an acceptable relative humidity; again there is a sharp increase in the relative humidity during unoccupied hours when the direct expansion unit was shut down. The increase in the relative humidity when the direct expansion units were not operating was contributed to the evaporation of the condensed water in the A/C coil drain pan. Data for 15 cfm/person intermittently and continuously for the A/C coils were taken; however, Downing and Bayer (1993) did not plot this set of data since the relative humidity was significantly higher than that for the 5 cfm/student continuously. When a dual-wheel desiccant unit was installed and operated at 15 cfm/student continuously during both occupied and unoccupied hours, the relative humidity remained relatively constant. Fischer (1996) does a complete economic analysis comparing desiccant units to direct expansion units providing 15 cfm per/person continuously.

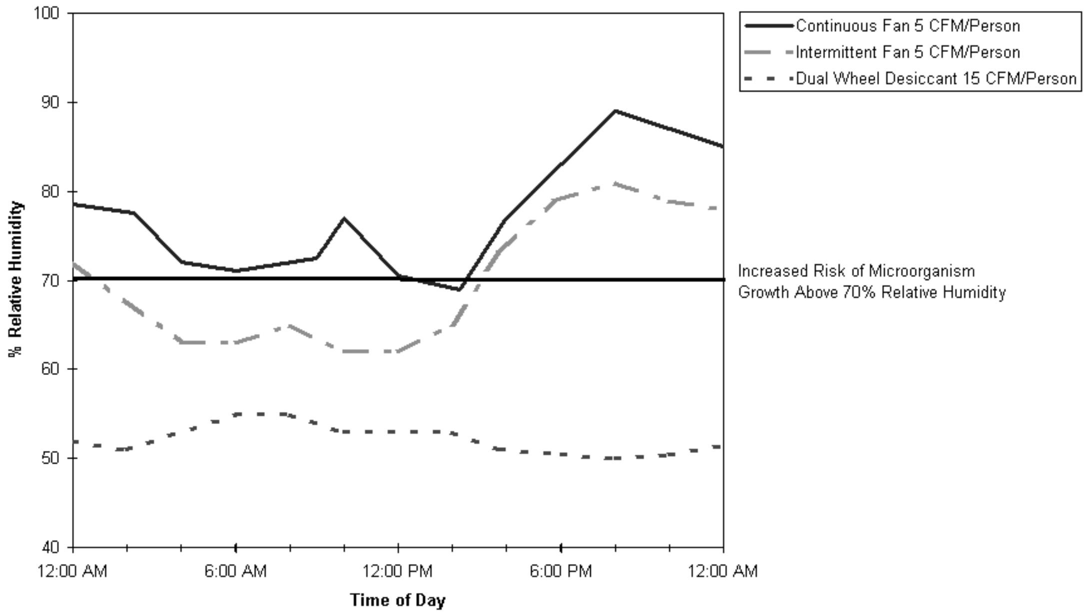

Figure 3.9 Daily Humidity Level Comparisons.

Desiccant systems are a convenient means to control the indoor relative humidity. As Downing and Bayer (1993) have shown, desiccant systems can supply larger quantities of fresh air without introducing an unacceptably high relative humidity to the indoor environment. Since desiccant systems remove the moisture from the process air stream through a vapor-phase mass transfer process (i.e., no condensation), there is little chance for the system to promote microorganism growth. A major limiting factor in desiccant systems is the initial cost; however, the added cost can be insignificant compared to the potential energy savings the unit can provide as well as the reduced health care costs due to better humidity (and microorganism) control (Fisher, 1996). Furthermore, the initial cost of a desiccant unit to handle high ventilation rates is roughly equivalent to purchasing a direct expansion unit that can handle the same ventilation rates (Fisher, 1996).

3.6 IAQ Pollutant and HVAC System Interactions

Considering the different parts of a standard commercial HVAC system, as illustrated in Figure 3.10, there are plenty of areas where both biological and non-biological contaminants can be found. For example, the cooling water, within chilled water HVAC systems, could potentially host a multitude of organic life such as bacteria and fungi. Meitz (1988) found blue-green algae, many types of fungi, and heterotrophic bacteria (which depend on other organisms for food) within chilled water lines. While these micro-organisms are not necessarily indicators of contamination, evidence from several microbiological studies show that these microorganisms are usually present with other contaminants (Meitz, 1988). To further illustrate this point, a study conducted into the ventilation systems of "moldy" office building by Morey et al. (1986) found that both condensate water and cooling tower water had elevated fungi and bacteria concentrations, on average 200 counts/mL and 20 million counts/mL, respectively. Since the samples collected consisted of both active and stagnant pools, water activity was not a factor. If the chilled water lines break, these contaminants could start colonizing hard to reach interior spaces of the building. Furthermore, the heat transfer capacity of the coils within the HVAC system can be compromised greatly due to the biofouling, increasing energy costs.

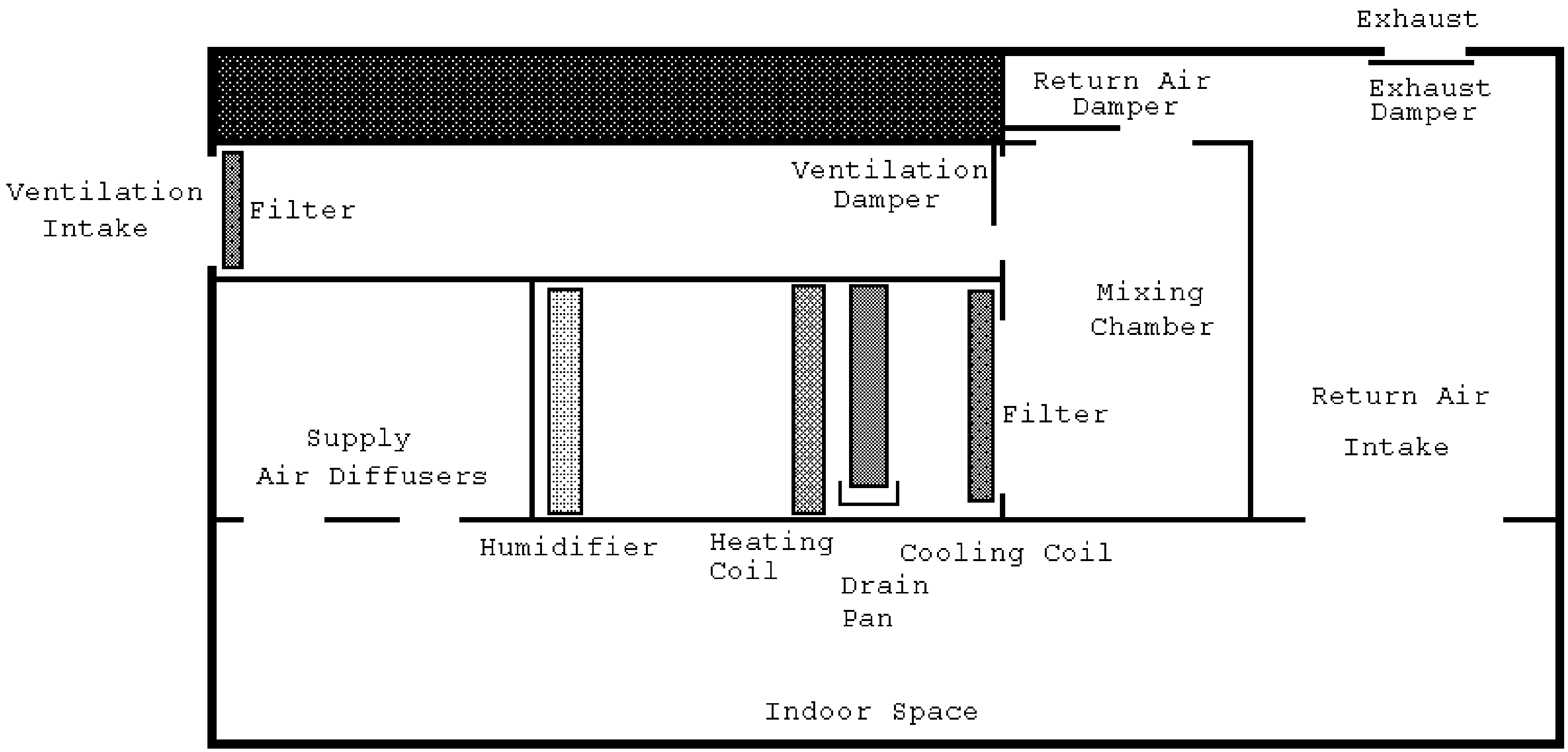

Figure 3.10 Diagram of a Typical Commercial HVAC System.

Even though the cooling water in the HVAC system should be considered for contamination, water sources often appear in other parts of the ventilation system. For example, air washers, which are used to thermally control the air while removing contaminants, can promote microbial growth due to readily available nutrients (dust collected by the washer) and plenty of water (the medium to remove the dust). Therefore, air washers will usually contaminate themselves. Another example is poor ductwork routing. A Finnish study (Pasanen et al., 1993) found that when ductwork was routed within unheated spaces, such as attics, during the winter, moisture would condense inside the ductwork. The moisture and temperature within the duct were such that fungi growth was sustained, but the fungi did not emit any spores. Then, at the onset of summer, the fungi began emitting spores into the indoor air with spore concentrations ranging from 40 counts/m^3 to 80 counts/m^3 (Pasanen et al., 1993).

Because water condensation frequently occurs in the HVAC ductwork, especially near diffusers, Morey (1995) looked into the fungal concentrations of building materials in which the condensate could make contact – the fiberglass insulation within the ductwork, ceiling tiles near the diffusers, and the carpeting underneath the diffusers. One of the most important findings of this study was that fungal counts could be quite high in the areas investigated. Furthermore, fiberglass insulation uses a urea-base adhesive to hold the fibers together with the backing. Urea-based adhesives, particularly urea-formaldehyde, have been found to sustain large amounts of microbial growth (Ezeonu et al., 1994). Combine the urea-based adhesives with the condensation that may form within the ductwork, then microbial problems at these locations can be significant. Studies have shown that several fungi could interact with the duct-material and produce MVOC's that may cause sick building syndrome (Bjurman, 1993 and Ezeonu et al. 1994).

In addition to the other HVAC problem areas, the coiling coils in HVAC systems may become infested with microorganisms as well. Morey and Williams (1991) found levels of several fungi over 2.5 million counts per gram within "dirty" insulation near the coiling coils of an HVAC system. Hugenholtz et al. (1995) investigated a biofilm containing 13 bacteria and fungi that were found on the evaporator of a direct expansion unit. Most of the species found in the biofilm were determined to have a high tolerance to desiccation stresses (i.e., they could survive being dehydrated and rehydrated). Furthermore, Rose et al. (2000) and Simmons et al. (1999) have shown that biofilms growing on coils are usually unnoticeable without the aid of a microscope, making identification of infected coils nearly impossible.

Due to the amount of dust that can accumulate on HVAC system filters, they can become a major feeding ground for microorganisms. Morey et al. (1986) found that shaking out filters gave off fungal counts of 62,000 to 70,000 counts/m^3. According to Morey et al., the high levels of dust can contribute to fungal growth within the system. Kemp et al. (1995) showed that the HVAC filters could act as a growth amplifier for microbial life by removing microbes as well as the dust. The close proximity of filters near the cooling coils also exposes this microorganism colony to the high moisture conditions that surround the cooling coil areas.

CHAPTER IV

REMEDIATION AND PREVENTION

The previous chapters have discussed the various indoor air pollutants, HVAC system components, and microbial problems that may occur within HVAC systems. This chapter will discuss the various remediation and prevention techniques that are currently available. The two focuses will be on HVAC system infiltration prevention – filtration, ultraviolet (UV) light, and antimicrobial duct surfaces – and humidity control. Other control mechanisms, such as microbial nutrition reduction through proper hygiene, are also addressed. While the vast majority of the remediation measures below are directed toward microbial growth, some techniques are applicable to nonbiological contaminants as well.

4.1 Investigating Indoor Air Quality Complaints

Before any building or system modifications can be recommended, a good understanding of the problems experienced by the building occupants is imperative. Once the symptoms are known, including the areas of greatest complaint, then a more detailed study of the building can take place. According to Bright et al. (1992), an investigation team would ideally consist of occupational health surgeons, HVAC engineers, and civil engineers. Collet et al. (1993) additionally recommend including architects (which may be able to replace the civil engineers) and industrial hygienists.

One of the most common means of determining symptoms experienced by the occupants is the use of questionnaires (Bright et al., 1992 and Collet et al., 1993). The questions asked range from demographic data (age, sex), psychosocial factors (stress), smoking habits, health problems and symptoms experienced, when these symptoms begin and end, location within the building, and office equipment in the vicinity. While not considered the most objective source of information, these questionnaires help to isolate the problematic areas of buildings.

After assessing the questionnaire data, a review of the building and systems design should be completed. This review can be performed either through a walkthrough of the building or by a review of the architectural and engineering plans; if possible, both of these investigations should be performed. During the walkthrough and review process, the investigators should have constant and clear communication with the building owners, occupants, and maintenance staff (Bright et al., 1992 and Collet et al., 1993). Additionally, this point in the investigation may include medical examinations and interviews of the building occupants (Bright et al., 1992).

After the questionnaire and initial assessment, Collet et al. (1993) recommend IAQ and thermal comfort monitoring, which includes monitoring the carbon monoxide levels, carbon dioxide levels, temperature, relative humidity, and suspended particles. Although not stated by Collet et al., the monitoring should include the measurement of bioaerosols, biological sampling of surfaces, and measuring the number of air changes per hour for each room and for the entire building. The ambient outside concentrations of the biological and chemical agents ought to be measured as well; if possible, these measurements should be taken as close to the ventilation intake as possible. The number of air changes per hour and carbon dioxide concentration will help the investigation team determine if the ventilation rate needs to be adjusted and by how much. The carbon monoxide levels are a measure of the combustion processes occurring within the building and how well the combustion processes are being ventilated. The temperature and relative humidity data can also be correlated to the occupants' reported symptoms, which can then assist in determining the effects of any microbiological problems. The suspended particle measurements determine the efficiency of the filters being used in the HVAC system as some studies have suggested that dust could be the cause of some asthma and allergy symptoms. Collet et al. (1993) recommend using quick-response electronic sensors to measure the temperature and relative humidity, nondispersive infrared and electrochemical analyzers for the measurement of carbon dioxide and carbon monoxide, respectively, and nephelometric monitors to measure the suspended particles.

After gathering the above information, the investigative team should compile it into a useful form. For example, the medical data can be cross-referenced to the occupants and locations within the building; since the IAQ and thermal comfort data are acquired at specific locations, the IAQ and comfort data can be cross-referenced to certain occupants. The medical symptoms can then be correlated to the IAQ and comfort data. In addition to the correlating the data to specific areas, building traffic pattern data may also need to be gathered and added to the analysis. After correlating these data, complaints can be shown to be either physical (the IAQ data verifies the medical symptoms) or psychological (the symptoms are not validated by the IAQ data). If there the complaints are shown to be physical, then the IAQ investigation team needs to develop remediation techniques to resolve the problems. If the complaints are shown to be psychological rather than physical, the investigation team may have to exercise some diplomacy and still develop remediation measures as if they were physical.

After developing and implementing the remediation measures, the team should perform at least one follow-up visit. Bright et al. (1992) recommend follow-up visits at one month, six months, and twelve months after the remediation measures have been implemented. These follow-ups should include recirculating the questionnaires and, if requested, resampling for IAQ pollutants and thermal comfort conditions. Depending on the results of the follow-up investigation, a more thorough investigation may be necessary.

4.2 Sources of Indoor Air Pollutants

Indoor air pollutants are commonly generated inside buildings and within building systems. Table 4.1 lists some common locations, the main sources at the location, and the most probable indoor air pollutants generated. The most susceptible locations are those that routinely have high relative humidity such as kitchens, bathrooms, and ventilation systems.

Table 4.1 Common Locations and Sources of Indoor Air Pollutants

Location and Sources	Pollutants
Air Conditioners and Refrigerators Drain pans, stagnant water	Bacteria, Fungi
Bathroom Showers, tubs, carpet, wallpaper, window coverings, cleaning supplies	Fungi, Bacteria, VOC's
Kitchen Cooking by-products, cleaning supplies, food preparation	VOC's, Fungi, Bacteria
Ventilation Ducts Interior duct insulation	Fungi, Bacteria
Humidifiers Water tank	Bacteria
Subterranean Rooms Improper drainage, chemical storage	Fungi, Bacteria, VOC's
Office Equipment Laser printers, photocopiers, personal computers	VOC's, Ozone
Other Building Locations Improperly placed vapor barriers, leaking plumbing, leaking roof, flood damage, cleaning supplies, floor coverings, building adhesives, paint	Fungi, Bacteria, VOC's

Since microbial growth is the most common pollutant, a closer look is warranted. All microorganisms that survive in the ambient environment require carbon, nitrogen, and water for growth. While each microorganism has different thermal requirements, most overlap within the human comfort zone (68 – 75 °F, 20 – 24 °C). Furthermore, the majority of microorganisms prefer relative humidity ranges of either 35 % and less or 75 % and greater. Therefore, microbial growth will be greatest where three requirements above are satisfied. Table 4.2 is a compilation of common microbial pollutants, health effects, primary sources, and remediation procedures. As this table illustrates, the common remediation methods are source removal, increased ventilation, humidity control, and routine maintenance. All of these remediation methods are discussed in the succeeding sections.

Table 4.2 Common Microbiological Pollutants, Health Effects, and Remediation

Living Source	**Airborne Units**	**Human Health Effects**	**Primary Sources**	**Common Remediation Methods**
Fungi	Organisms, spores, metabolic by-products (MVOC's)	Asthma, rhinitis, hypersensitivity pneumonitis, infectious disease	Damp environmental surfaces, outdoor air, damp surfaces, fiberglass insulation	Removal of contaminated material, cleaning surfaces, increased ventilation, proper maintenance of ventilation and conditioning systems
Bacteria	Organisms, metabolic products	Hypersensitivity pneumonitis, person-to-person infectious disease, building related infectious disease	Water sources, damp surfaces, fiberglass insulation, human and animal hosts	Routine cleaning of water systems, relocation of ventilation intakes, quarantine infected host
Viruses	Organisms	Person-to-person infectious disease	Human and animal hosts	Quarantine infected host , increased ventilation
Dust Mites	Feces	Asthma, rhinitis	Mattresses, bedding, upholstered furniture, dust, thick carpetting	Removal of contaminated material, vacuuming with HEPA filters, reduction of ambient relative humidity

4.3 Proper Hygiene

One of the easiest and most cost effective remediation measures is proper hygiene, which is defined as maintaining clean surfaces within buildings. By maintaining clean surfaces, several different prevention and remediation mechanisms work together. Cleaning helps to prevent large buildups of microorganism nutrients – usually carbon sources. Additionally, since cleaning usually involves some sort rag or sponge wiping the surface, the cleaning procedure will also help to breakup and/or remove biofilms and individual microorganisms. Furthermore, most cleaners are, to some extent, desiccators and will kill/neutralize microorganisms that have low tolerance to desiccation. Some of the more common places within buildings to find microorganisms are showers and baths because of the plethora of nutrients (dead skin and soap scum), water, and air.

Furthermore, if surfaces are left unkempt for long periods of time, the possibility of biofilms forming on the surface are increased dramatically. Since biofilms will be more mature on these unclean surfaces, the potential for removing the microorganisms will be significantly reduced. If the surface is porous, there is a potential for the biofilm to spread into the recesses of the material. Then when the biofilm is removed from all visible surfaces, the biofilm is commonly seen to grow from the pores and repopulate the surface of the material. This has been well documented with drywall in bathrooms and kitchens, where signs of mold growth were visible on the room side of the drywall. When the visible mold growths were cleaned, the mold reappeared quickly. In several cases, when the drywall was removed, there were large mold colonies on the backside of the drywall that were trying to grow into the room. In these cases, the only solution is to replace the material. While cleaning the surfaces does not help in these cases, they highlight the need to maintain a clean environment.

4.4 Filter Replacement and Efficiency

Proper filter selection and use can be as easily implemented as proper cleaning. Economics dictates that the most commonly used filters are the cheapest ones. The cheapest filters, at best, are about 20 % effective at removing dust particles. If a filter only captures about 20 % of dust particles, which are generally larger in diameter than microorganisms, it cannot effectively reduce the amount of microbes within the HVAC system. Also, the accumulated dust on filters can potentially become sources of microbial growth and emission. While the use of high efficiency HEPA filters would be ideal, the maintenance costs associated with HEPA filters are usually not justified, except for health care facilities. However, filters in the 50% efficiency range could be economically justified in buildings where indoor air quality complaints have been made and should help to reduce the amount of microbes within the HVAC system. In addition to the filter efficiency, filter material is an important criterion for filter selection. Kemp et al. (1995) tested three different types of filters – a glass fiber filter, a polymer fiber filter, and an electrostatic filter – to determine if any particular filter would promote growth. These tests showed that the two fiber filters had significant microbial growth on both sides of the filter while the electrostatic filter killed 90% of the microorganisms that attached to it. Regardless of the filtration efficiency or material, routine filter replacement (or cleaning for electrostatic filters) will help ensure that the HVAC system is kept clean.

4.5 Ventilation

The normal remediation method for volatile organic compounds is to increase ventilation. Problems associated with increased ventilation are the need for increased humidity control and increased filtration. The increase in humidity control is due to the larger latent loads that an increase in ventilation usually includes. Furthermore, many HVAC systems have been designed to handle the old ASHRAE Standard 62-1982 of 5 cfm/person and could potentially result in having to replace the main air handling unit to meet the required latent load. Ventilation does not necessarily need to be done mechanically; some buildings, such as residences, can benefit from the use of passive ventilation strategies.

4.6 Ductwork and Fiberglass Insulation

Common practice in HVAC installation has been to put fiberglass insulation on the interior of the ductwork. In recent years, this practice has been frowned upon by IAQ community; however, several buildings still have ductwork installed in this fashion. Fiberglass is usually held together with urea-based resins that are readily available nutrition sources for microorganisms. In addition to the nutrients, fiberglass, when installed inside ductwork, is a source of high shear stress within the duct and biofilms form more readily in high shear stress environments (Donlan and Costerton, 2002). Furthermore, Pasanen et al. (1993) has shown that ductwork can be susceptible to condensing the moisture in the air during the winter season. Therefore, ductwork with insulation on the inside of the ductwork has several strikes against it – readily forms biofilms, easy access to nutrients, and easy access to water. Combine these with the easy access to nitrogen in the air and this ductwork becomes an easy environment for microorganism colonization.

Several different remediation measures have been developed to resolve these problems. For example, fiberglass insulation with an antimicrobial surface for mounting inside the ductwork has been introduced by several companies. Some problems with this solution exist. First, if the antimicrobial surface is torn, then the microorganisms have direct access to the fiberglass, and the original problem reoccurs. Second, microorganisms will usually adapt to their surroundings, and the antimicrobial surface will loose its effectiveness. Another solution is to attach the fiberglass insulation to the outside of the ductwork. However, this may expose the insulation to environmental conditions that would increase the deterioration of the ductwork. Furthermore, the interior duct surface would be left bare and prone to microbial infestation as well (Ahearn et al., 1991; Rose et al., 2000; and Simmons et al. 1999). To correct this problem, Seal-Tite has introduced ductwork made from AK Steel's silver ion epoxy coated steel (Mazurkiewicz, 2002) since silver will help to prevent microbial attachment to surfaces.

4.7 Ultraviolet Light

Ultraviolet (UV) light can be used to kill microorganisms; however, it is dependent on several factors such as dosage (intensity) and amount of exposure. UV light is usually implemented within ductwork near the building's ventilation intake; however, placement just after the filters would be logical as well, especially if the system does not have ventilation intakes. Intensity can be controlled by controlling the power of the UV bulb. The amount of exposure is easily controlled by the number of UV lights placed together within the duct system. Ultraviolet light works by submitting microorganisms to an intense radiation blast that alters their protein synthesis genes. This means that the microbes cannot generate the proteins that are necessary for sustaining life and die. UV, however, is only a surface effect. If a biofilm passes under a UV light, the outside layer may die out, but the interior layers are unaffected. Therefore, UV cannot guarantee complete removal of microorganisms entering the HVAC system, but can reduce the amount present.

4.8 Building Adhesives

Eliminating the use of building adhesives is nearly impossible as most modern furniture and decorative elements contain significant amounts of adhesive; however, the use of these materials can be significantly reduced. The most commonly used adhesives are urea-based resins such as urea-formaldehyde, urea-phenolic, and glyoxal resins. According to Ezeonu et al. (1995), these resins are very good sources of nutrition for microorganisms. Some common applications for these urea-based resins include fiberglass insulation, laminated layers in plywood, construction adhesive, wallpaper paste, and contact cement. In modern construction and interior design, these materials are frequently used. Wallpaper manufacturers have been applying antimicrobial coatings on wallpaper over the past several years; however, this does not always prevent microbial infestation of wallpaper application, particularly when the wallpaper starts pealing and the glue is exposed to the environment. Most plywood surfaces are either painted or covered with other materials (such as wood veneer, tile, or padded upholstery). In most instances, the adhesive compounds are not exposed directly to the environment, and the chance of microbial infestation is low.

4.9 Humidity Control

Harriman et al (2000) stress the need for moisture load control in order to prevent negative effects of water intrusion, condensation, and humidity development. Humidity control may be accomplished by using direct expansion (DX) units, desiccant dehumid-ification units, passive ventilation, mechanical ventilation, humidification units, or any combination of these. As the preceding narrative has shown, most indoor air pollutant effects are strongly influenced by the relative humidity. Figure 4.1 shows the effect of relative humidity on common indoor air pollutants and human ailments. As illustrated in this figure, the optimum relative humidity range is 40 – 60 %. For this reason, common practice is to design humidification systems to maintain a 50 % relative humidity; however, the needs of the space will determine the designed humidity set-point. The two most significant pollutants in the 40 – 50 % relative humidity range are chemical interactions and ozone production. Chemical interactions can be minimized by storing chemicals outside buildings (source removal) and increasing ventilation. The most common source of ozone production is office equipment; therefore, ozone production cannot be controlled by source removal as easily as chemical interactions.

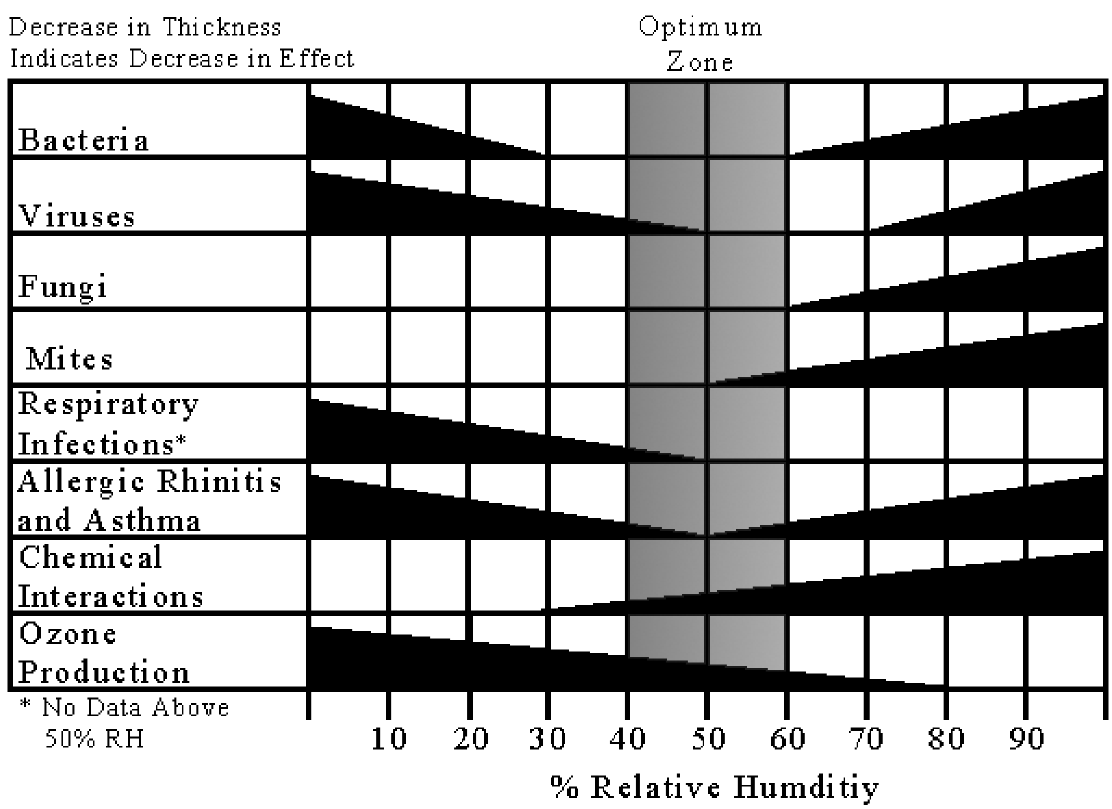

Figure 4.1 Relative Humidity Effects on Indoor Air Pollutants and Human Illnesses

In addition to using dedicated systems, building materials can be incorporated into humidity control as well. Hygroscopically active materials are a class of materials that could be used for humidity control. Hygroscopically active materials are defined as materials that are able to adsorb and desorb moisture from the ambient air (Baughman and Arens, 1996). Some examples of hygroscopically active materials include wood, wool-based products, and cement bonded wood fiber (CBWF). The exact nature of these materials is not fully understood. For example, woods are known to prevent microbial growth; however, natural fibers tend to promote dust mite growth. CBWF has "an interesting and unique mix of vapor permeability and vapor storage capacity," according to Straube and deGraauw (2001). CBWF has been known to provide a healthier indoor environment; however, this research by Straube and deGraauw has been one of the first attempts to learn why it provides a healthier indoor environment. The research shows that hygroscopically active materials may be able to help prevent mold and fungi problems during peak relative humidity conditions by adsorbing some of the moisture from the ambient air. West and Hansen (1992) found that hygroscopically active materials can influence the indoor relative humidity by as much as 15 – 20 %. The use of hygroscopically active materials may help in controlling the space relative humidity in "wet" rooms such as kitchens, bathrooms, and laundries; however, only materials with known hygroscopic properties should be used. More research in this area is necessary before the widespread use of hygroscopically active materials can be recommended as a general approach to helping control the indoor relative humidity.

CHAPTER V

CONCLUSIONS

Microorganisms, while varied in their requirements, do share several similarities. All require some form of nutrition, usually carbon sources, plenty of nitrogen (air) and water. While microorganisms can potentially get the water they need from the water vapor in air, the preferred water source is usually surface condensation. Readily available nutrient sources include adhesives, soap scum, and skin. Furthermore, most microorganisms prefer the same temperature environment as humans, which make controlling microorganisms difficult. The best method of controlling microbial growth will limit the amount of nutrients available for the microorganisms and maintain a relative humidity between 40 % and 60 % relative humidity (as illustrated in Figure 4.1). Other measures, such as ultraviolet light and antimicrobial coatings, may help prevent major microbial problems, but these measures will tend to loose their effect over time.

The only solutions for controlling volatile organic compounds are either source removal or dilution. With source removal, chemical storage would be removed from the main building, and combustion sources would be isolated from the main building. Dilution calls for an increase in ventilation to maintain VOC concentrations at an acceptable level. Dilution is best used for reducing the effects of combustion sources (when they cannot be isolated) and occupant-generated pollutants such as carbon dioxide.

The best way to avoid IAQ problems is to design the building to incorporate pollutant-minimizing systems from the beginning. If no other measures are taken, maintaining a clean environment and increasing filters are necessary. According to Kemp et al. (1995), electrostatic filters are highly recommended. A well-designed building ventilation system will incorporate measures to minimize both microbial and nonbiological agent sources. Ventilation, in most cases, needs to be increased. Equation 3.1 can be used to determine the amount of ventilation a building needs. To make ventilation more economical, demand-controlled ventilation should be used whenever possible. For temperature control, the conventional cooling coil technology is still recommended. However, cooling coil technology should not be used for humidity control. Desiccant units with judicious use of hygroscopically active materials are sufficient to maintain relative humidity in the desired 40 – 60 % range. With the current state of the art and knowledge, the optimum system would be one that incorporates all of the above recommendations and uses both ultraviolet light and antimicrobial surfaces to further reduce microbiological problems.

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