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Causes of Indoor Air Quality Problems in Schools

Summary of Scientific Research

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Charlene W. Bayer
Sidney A. Crow
John Fischer

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CAUSES OF INDOOR AIR QUALITY PROBLEMS IN SCHOOLS

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SUMMARY OF SCIENTIFIC RESEARCH

Charlene W. Bayer, Ph.D., *Principal Research Scientist and Branch Head*
Georgia Tech Research Institute, Atlanta

Sidney A. Crow, Ph.D., *Professor, Biology Department*
Georgia State University, Atlanta

John Fischer, *Technology Consultant*
SEMCO, Inc., Columbia, Mo.

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❖ ABBREVIATIONS AND ACRONYMS

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
DWERS	dual-wheel total energy recovery system
HVAC	heating, ventilation, and air-conditioning
IAQ	indoor air quality
MVOC	microbial volatile organic compound
PM_{10}	particulate matter of <10 μm diam
$PM_{2.5}$	particulate matter of <2.5 μm diam
SBS	sick building syndrome
TERS	single-wheel total energy recovery system
VAV	variable air volume
VOC	volatile organic compound

1 ❖ SCHOOL FACILITIES AND INDOOR AIR QUALITY

The U.S. government's General Accounting Office issued reports stating that one in five schools in the United States has problems with indoor air quality (IAQ) (GAO 1995, 1996). According to the same studies, 36% of the schools surveyed listed HVAC systems as a "less-than-adequate building feature." The reports also suggested that there appears to be a correlation between unsatisfactory IAQ and the proportion of a school's students coming from low-income households.

Fourteen states regulate one or more environmental factors related to IAQ in schools (ELI 1996). These are

- pesticide application: Arizona, Louisiana, Michigan, Montana, Tennessee, and Texas;
- urea-formaldehyde insulation: California and Connecticut;
- ventilation standards in schools, public buildings, or workplaces: California, Connecticut, Maine, New Jersey, and New Hampshire;
- mandatory consideration of IAQ in school energy conservation efforts: California and Maine;
- state review or evaluation of school IAQ: Florida, Maine, and New Hampshire;
- state assistance to local health departments in adopting IAQ programs in public buildings: Wisconsin;
- mandatory school IAQ programs and best practices requirements to improve IAQ in new school buildings: Washington.

One in five U.S. schools have indoor air quality (IAQ) problems, a real concern in schools because

- *children are still developing physically and are more greatly affected by pollutants;*
- *the number of children with asthma is up 49% since 1982;*
- *children up to the age of 10 have three times as many colds as adults;*
- *poor IAQ can lead to drowsiness, headaches, and a lack of concentration.*

Most other states are less proactive and are therefore dependent upon national building standards such as the Southern Building Code, industry standards such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62-1989, and the professional judgment of architects, consulting engineers, and state and local school facility managers. These decision makers are faced with many priorities other than IAQ concerns, all of which compete for what is often a limited budget.

Bascom (1997) states that “schools are facing two epidemics: an epidemic of deteriorating facilities and an epidemic of asthma among children.” He notes that while clinicians are trying to instruct schools regarding environmental control measures for children with asthma, these clinicians have little information about the conditions and practical means in schools. The schools are ill-equipped to receive the recommendations, assess their reasonableness, and effect the recommendations at a reasonable cost. Bascom calls for the development of task forces to assemble the necessary expertise to solve these problems. He points to the need for a controlled IAQ research study so that effective IAQ plans can be developed and implemented.

There are many reasons that IAQ should be considered a top priority in the school environment. One is that children are still developing physically and are more likely to suffer the consequences of indoor pollutants. Another is that the number of children suffering from asthma is up 49% since 1982, according to the American Lung Association (Sundell and Lindvall 1993). Asthma is the principal cause of school absences, accounting for 20% of lost school days in elementary and high schools (Richards 1986). Richards also notes that allergic disease (nasal allergy, asthma, and other allergies) is the “number one” chronic childhood illness, accounting for one-third of all chronic conditions occurring annually and affecting 20% of school children. Children from birth to age 10 have three times as many colds as adults (Tyrrell 1965, p. 19). School facilities, by design, are densely populated, making the task of maintaining an acceptable IAQ more difficult than in many other types of facilities. Another consideration is that the sole purpose of a school facility is to foster the learning process, which is impacted directly by the quality of the indoor environment (HPAC 1990; Dozier 1992; Boone et al. 1997). Finally, most individuals have experienced drowsiness, lack of concentration, or headaches in a classroom or auditorium environment and understand the impact these symptoms have on comprehension and motivation. ❖

2 ❖ BACKGROUND

In the modern urban setting, most individuals spend about 80% of their time indoors and are therefore exposed to the indoor environment to a much greater extent than to the outdoors (Lebowitz 1992). Concomitant with this increased habitation in urban buildings, there have been numerous reports of adverse health effects related to IAQ (“sick buildings”). Most of these buildings were built in the last two decades and were constructed to be energy-efficient.

The quality of air in the indoor environment can be altered by a number of factors: release of volatile compounds from furnishings, floor and wall coverings, and other finishing materials or machinery; inadequate ventilation; poor temperature and humidity control; re-entrainment of outdoor volatile organic compounds (VOCs); and the contamination of the indoor environment by microbes (particularly fungi). Armstrong Laboratory (1992) found that the three most frequent causes of IAQ are (1) inadequate design and/or maintenance of the heating, ventilation, and air-conditioning (HVAC) system, (2) a shortage of fresh air, and (3) lack of humidity control. A similar study by the National Institute for Occupational Safety and Health (NIOSH 1989) recognized inadequate ventilation as the most frequent source of IAQ problems in the work environment (52% of the time).

A study by Armstrong Laboratory, at Brooks Air Force Base, Texas, found that the three most frequent causes of unacceptable indoor air quality (IAQ) are (1) inadequate design and/or maintenance of the heating, ventilation, and air-conditioning (HVAC) system, (2) a shortage of fresh air, and (3) lack of humidity control.

Poor IAQ due to microbial contamination can be the result of the complex interactions of physical, chemical, and biological factors. Harmful fungal populations, once established in the HVAC system or occupied space of a modern building, may episodically produce or intensify what is known as sick building syndrome (SBS) (Cummings and Withers 1998). Indeed, SBS caused by fungi may be more enduring and recalcitrant to treatment than SBS from multiple chemical exposures (Andrae 1988). An understanding of the microbial ecology of the indoor environment is crucial to ultimately resolving many IAQ problems. The incidence of

SBS related to multiple chemical sensitivity versus bioaerosols (aerosolized microbes), or the contribution of the microorganisms to the chemical sensitivities, is not yet understood.

If the inhabitants of a building exhibit similar symptoms of a clearly defined disease with a nature and time of onset that can be related to building occupancy, the disease is generally referred to as “building-related illness.” Once the SBS has been allowed to elevate to this level, buildings are typically evacuated and the costs associated with disruption of the building occupants, identification of the source of the problem, and eventual remediation can be significant.

Understanding the primary causes of IAQ problems and how controllable factors—proper HVAC system design, allocation of adequate outdoor air, proper filtration, effective humidity control, and routine maintenance—can avert the problems may help all building owners, operators, and occupants to be more productive (Arens and Baughman 1996). This paper provides a comprehensive summary of IAQ research that has been conducted in various types of facilities. However, it focuses primarily on school facilities because, for numerous reasons that will become evident, they are far more susceptible to developing IAQ problems than most other types of facilities; and the occupants, children, are more significantly affected than adults (EPA 1998). ❖

3 ❖ IAQ INVESTIGATIONS CONDUCTED IN SCHOOL FACILITIES

Daisey and Angell (1998) conducted a survey and critical review of the existing published literature and reports on IAQ, ventilation, and building-related health problems in schools. They found that the types of health symptoms reported in schools are very similar to those defined as SBS, although this finding may be due, at least in part, to the type of health symptom questionnaires used. Some of the symptoms (e.g., wheezing) are indicative of asthma. In the studies in which “complaint” and “noncomplaint” buildings were compared, complaint buildings usually had a higher rate of health-related symptoms.[1]

Formaldehyde, total VOCs, CO_2, and bioaerosols were the most commonly measured pollutants in schools. Most of the formaldehyde measurements made in the United States were in complaint schools but were still generally below 0.05 ppm. The measurements of the other pollutants were too limited to draw conclusions as to the prevalence of indoor concentrations of concern, even in problem schools. However, there was some evidence that microbiological pollutants are of particular concern. The few scientific studies on causes of symptoms in complaint schools indicate that exposure to molds and allergens in schools contributes to asthma, SBS, and other respiratory symptoms. Other indoor pollutants, such as VOCs and aldehydes, have been investigated to only a very limited extent, although there are reasons to suspect that they may also contribute to the prevalence of health-related symptoms in schools.

The major building-related problem identified was inadequate outdoor air ventilation. Water damage to the building shells of schools, leading in turn to mold contamination and growth, was the second most frequently reported building-related problem. The root cause of many of the ventilation and water-damage problems in the schools was inadequate and/or deferred maintenance of school buildings and HVAC systems.

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[1] Complaint buildings are those for which an abnormal number of complaints are made regarding the quality of the indoor air.

Daisey and Angell concluded that there is now considerable qualitative information on health complaints, ventilation, and IAQ problems in complaint schools. It is unknown what fraction of schools are experiencing IAQ and ventilation problems and related health problems. There is also a lack of the scientifically rigorous and quantitative information on causal relationships between health symptoms, exposure, and dose-response relationships that is needed to establish health standards for the protection of children in schools. The effectiveness and the costs and benefits of various remedial actions undertaken to solve problems in specific schools remain largely unknown.

Daisey and Angell found that the major building-related problems in "complaint" schools were inadequate outdoor ventilation, followed by water damage to building shells that set up conditions for mold contamination and growth.

The report recommended the following research:

- Determine more quantitatively the degree to which IAQ problems in schools increase asthma, SBS symptoms, and absentee rates of students.
- Identify the specific agents that cause health effects and determine exposure- and dose-response relationships for those pollutants that are the most significantly related to health symptoms.
- Determine whether learning can be significantly increased through improved IAQ.
- Determine the cost-effectiveness of various remediation measures undertaken to solve problems in complaint schools through intervention studies in which changes in health symptoms and test scores are measured before and after remediation.
- Determine the costs of deferred building maintenance with respect to health and learning in students.
- Determine the viability of using CO_2 detectors and other types of sensors to routinely control ventilation and to provide an indication of inadequate ventilation.
- Develop improved sampling and analysis methods for bioaerosols.
- Develop low-cost samplers for measuring 6-hour exposures to other key indoor pollutants, such as aldehydes, that may be contributing to the kinds of symptoms observed in problem schools.

The U.S. Environmental Protection Agency (EPA 1998) is formulating a major study of IAQ in school buildings to provide baseline IAQ data. The study is to be similar to the BASE study (Womble et al. 1993) on office buildings, following a similar protocol. Six basic activities have been proposed:

- school selection representing both public and private schools;
- physical characterization of the buildings in terms of location, physical structure, ventilation, occupant density, occupant activities, and potential indoor pollutant sources associated with special use areas;
- definition of building study areas and random selection of four study areas for more extensive evaluation;
- monitoring for one week in the study areas to generate data on HVAC operation, environmental problems, and comfort factors using standard procedures and good quality assurance/quality control practices;
- administration of an occupant questionnaire to all adult occupants; and
- development of a publicly accessible database of study results.

Parameters proposed for monitoring include

- temperature, relative humidity, sound level, and illuminance;
- air pollutants [CO_2, CO, inhalable particles ($PM_{2.5}$ and PM_{10}), VOCs, formaldehyde, bioaerosols, radon];
- HVAC supply measurements (airflow rate, air temperature, air relative humidity);
- percentage and rate of outdoor air intake;
- exhaust fan and supply diffuser airflow rates; and
- supply diffuser parameters (temperature, relative humidity, and CO_2).

The protocol is currently in a draft form and is not to be cited or quoted specifically.

Downing and Bayer (1993) investigated the relationship between ventilation rate and IAQ in classrooms. Samples were collected and analyzed for VOCs, formaldehyde, CO_2, temperature, and humidity. Downing and Bayer confirmed in this study that 15 cfm per student of outdoor air was required to maintain CO_2 concentrations at levels below 1000 ppm. The recommendation was made that classrooms, both new and existing, be provided with at least 15 cfm per student of outdoor air on a continuous basis during school hours. It was found that VOC concentrations exceeded 1000 $\mu g/m^3$ when only 5 cfm per student was provided, even on a continuous basis. Tucker (1986) indicated that this level of VOCs is an indication of potential IAQ problems.

Downing and Bayer also measured space humidity as a function of the operating mode of packaged rooftop equipment compared with humidity levels maintained with a system utilizing a dual-wheel total energy recovery system (DWERS) (see Fig. 1). Humidity measurements collected over time for a school that had experienced serious microbial and IAQ problems showed that even with only 5 cfm per student being provided on a continuous basis, the space relative humidity

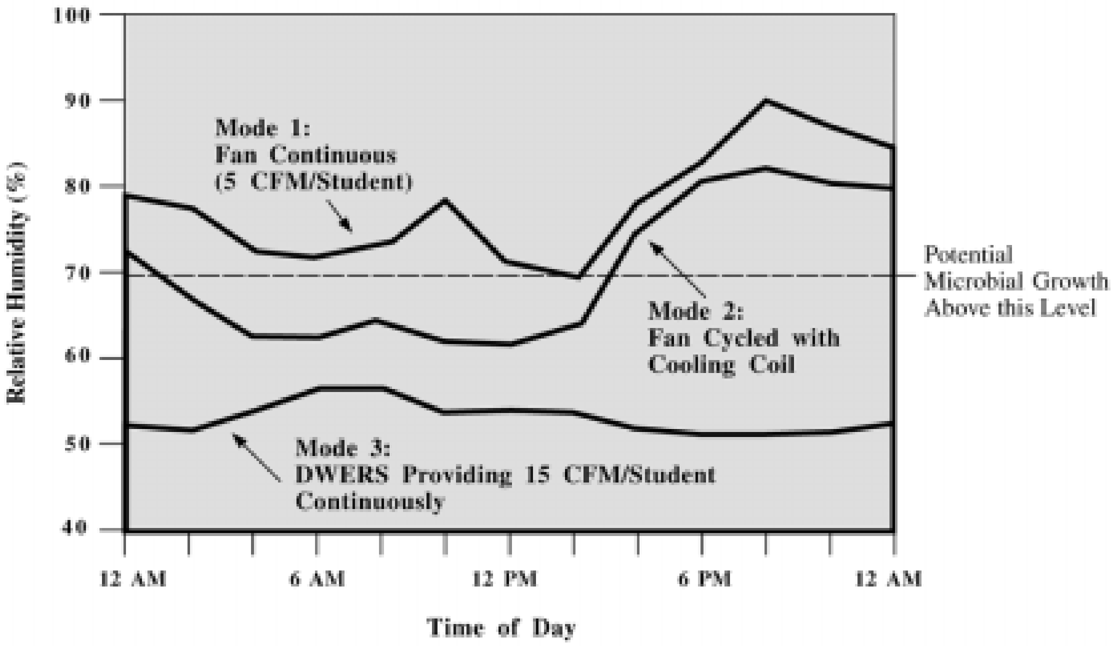

Fig. 1: Space humidity measured by Downing at three operating modes with and without the dual-wheel total energy recovery systems, showing lack of humidity control with conventional packaged HVAC units.

exceeded 80% for an extended period of time and averaged well over 70% during the investigation. When the fan was cycled with the cooling coil, the average space humidity dropped somewhat to approximately 70%, but it still exceeded 80% during the evening hours. With the DWERS maintaining the humidity content of the continuously supplied outdoor air, the space relative humidity averaged 53% and remained below 58% throughout the investigation.

Downing and Bayer reported that before the school was retrofitted with a DWERS, there was visible mold growth on building surfaces, carpeting, and books. The IAQ complaints and illnesses included respiratory and allergy problems, headaches, and lethargy. The HVAC system modification, which provided increased outdoor air quantities on a continuous basis while controlling space humidity, eliminated both the mold and the IAQ complaints by the teachers and students. This finding was confirmed through follow-up interviews by Downing and Bayer with a number of the teachers who had complained the most about the building's IAQ prior to the HVAC system retrofit.

In a school studied by Downing and Bayer, there was visible mold on building surfaces before retrofit. With a DWERS installed, average relative humidity dropped from 80% to 53%.

Bayer, Crow, and Noble (1995) reported on case studies conducted in five school systems in Georgia. In each of these schools, the students and teachers were experiencing rashes and respiratory illnesses. In each of the schools, microbial amplification was identified, and *Cladosporium* sp. was the most prevalent fungi found. Although atopic dermatitis has been reported to be relatively rare, one cause may be contact with molds such as *Alternaria*, *Cladosporium*, and *Aspergillus* in atopic individuals (Flannigan and Morey 1996). Bayer, Crow, and Noble also confirmed, via comparison of field results with laboratory studies, that many of the detected VOCs were microbial in origin.

Bayer (unpublished results) investigated IAQ problems in a southern school that had had to conduct an emergency evacuation because of strong odors and visible microbial growth. The school had to be abandoned within a few weeks after completion of a massive renovation that included new rooftop HVAC units, new carpeting, furnishings, painting, and so on. The carpet was covered with visible microbial growth and had a strong cinnamon odor in the most contaminated areas. Investigation revealed that water was condensing under the carpet on the concrete slab, as a result of the poor humidity control within the building. Using environmental chamber technology to simulate ongoing conditions in the school, Bayer found that the carpet adhesive would reactivate to a wet state whenever it was exposed to humidities greater than 75% for a period of several hours. The adhesive would reset to a hardened state when the humidity was lowered below 75% for several hours. When the adhesive was wet, strong solvent-type odors were emitted. The biocide present in the adhesive was designed to prevent microbial growth only in the sealed container before use; it was not able to prevent microbial growth in this cycling wet-dry-wet state. Without biocide protection, the carpet adhesive was an excellent nutrient base for microbial growth. The result was excessive amounts of microbial growth. The volatile emissions from the microbes were very strong: total VOC levels in the school exceeded 23,000 $\mu g/m^3$. The hexane levels exceeded 13,000 $\mu g/m^3$.

Although schools are prime candidates for fungal colonization, few studies have systematically examined the mycoflora of school buildings. Crow et al. (1993, 1994); Crow, Ahearn, and Noble (1995); Bayer and Crow (1992); Bayer, Crow, and Noble (1995); and Downing and Bayer (1993) have examined a number of buildings, including primary and secondary schools and university buildings. Samples represent a single collection of airborne viable samples from sites of amplification where fungal colonies were growing on surfaces within the building.

Crow et al. (1994) reported on two schools in a series of ten buildings sampled for airborne fungi. Both schools had both complaint and control sites. The first school had humidities of 58 to 61% during the test period. The viable fungal counts were 140 to 1615 cfu/m^3. Populations were dominated by species of *Cladosporium* and *Penicillium*. The second school had relative humidities of approximately 60 to 63% during the test period. This school had experienced obvious humidity control problems, indicated by sagging ceiling tiles and evidence of water condensation; and it yielded extremely high fungi numbers (735 to 5180 cfu/m^3) found on a variety of media. The dominant species were again *Cladosporium* and *Penicillium*.

In a second paper Crow, Ahearn, and Noble (1995) discussed three additional schools. The viable counts of airborne fungi were lower (35 to 1280 cfu/m^3) than those described for the previous schools. Dominant species were *Cladosporium* and *Penicillium*. At three additional schools sampled (unpublished data), airborne counts were in similar ranges and were generally dominated by *Cladosporium* and *Penicillium*. Clearly, variations in seasonal occurrence of outdoor fungi can confuse the interpretation of indoor air counts. Critical seasonal studies coupled with sophisticated data on humidity and the nature of volatiles will help clarify the meaning of airborne viable counts. Understanding of the basic physiological phenomena in microbes and the influence of environmental parameters on variation in basic processes, such as the formation of conidia and volatiles and their subsequent release, will clarify the etiology of SBS.

Bartlett, Kennedy, and Brauer (1998) recently conducted one of the few statistically significant IAQ investigations of schools. These researchers investigated IAQ in terms of microbial contamination (focusing on mesophilic and thermophilic fungi), CO_2, temperature, humidity, and air change rates in 39 schools in British Columbia. The 39 schools were randomized into three identifiable sampling periods—winter, spring, and fall. Two sampling cycles were required to investigate all of the schools. They found that the outdoor concentration of mesophilic fungi was statistically different from the indoor concentration. There was a seasonal correlation with concentrations of the fungi, and the winter indoor and outdoor counts were lower than either the spring or fall counts. Twenty-eight percent of the classrooms studied had culturable fungal concentrations greater than 500 cfu/m^3. The xerophilic fungi (those able to grow with reduced biologically available water) were present in greater concentrations in the fall. Xerophilic fungi are potential colonizers of building materials and potential allergens. Some xerophilic genera are suspected of being contributors to fungal allergic responses.

In Canadian schools studied by Bartlett, Kennedy, and Brauer, 71% of the classrooms failed to meet the ASHRAE ventilation standard, and 45% of the classrooms had average CO_2 concentrations above the ASHRAE maximum limit of 1000 ppm.

The apparent failure, found by Bartlett, Kennedy, and Brauer, of school ventilation systems to filter out fungi originating from the outside could allow for increased fungal exposure to susceptible individuals. Seventy-one percent of the classrooms failed to meet the ASHRAE 62-1989 ventilation standard. Forty-five percent of the classrooms had average CO_2 concentrations greater than 1000 ppm. The air exchange rates were lower in winter, when the HVAC systems were set at the minimum outside air supply level by the school facilities managers to reduce energy usage or avoid dumping cold air on the space occupants. The mean relative humidity level during the winter season was 36.9%. Bartlett, Kennedy, and Brauer concluded that the combination of the lower relative humidity and the inefficient ventilation, particularly in the winter season, may contribute to the spread of airborne infectious diseases that are common in classroom settings.

Mouilleseaux, Squinazi, and Festy (1993) conducted a microbial characterization of the indoor air in the classrooms in ten primary and nursery schools in Paris. The average aerobic bacteria count was 3000 cfu/m^3. They found that 32.7% of the analyzed samples contained *Staphylococcus aureus* (a germ indicative of human mucous/cutaneous contamination), 6.2% contained enterobacteria (a marker of faecal/hydrotelluric air contamination), and 50.6% contained thermotolerant *Streptococcus* (a marker of faecal/hydrotelluric air contamination). The average fungal counts were 100 cfu/m^3, and yeasts were 20 cfu/m^3. The fungal flora were polymorphic.

Airborne microbial contamination in naturally and mechanically ventilated buildings was studied by Maroni et al. (1993). These buildings included ten schools and seven office buildings. Maroni et al. did not find major differences in detected fungi between naturally and mechanically ventilated buildings. However, in the mechanically ventilated buildings, they did find a significant correlation between microorganisms and the relative humidity in wintertime, a negative correlation between bacteria and particulate matter in summertime, and a positive correlation between bacteria and temperature in summertime. They also found a weak correlation between total VOCs and fungi in the schools.

Smedje, Norback, and Edling (1997) studied the perceptions of school occupants of the IAQ in their schools. Data on subjective air quality, domestic exposures, and health aspects were gathered via questionnaires sent to all school employees in 38 schools (1410 people in all) in Sweden. Exposure data were gathered by classroom monitoring of temperature, relative humidity, rate of air exchange, CO_2, CO, NO_2, formaldehyde, other VOCs, respirable dust, molds, bacteria, settled dust, and mite allergens. The questionnaires indicated that 53% of the school occupants perceived the IAQ in their school as bad or very bad. The younger staff were more dissatisfied than older personnel. Also, those from homes with no tobacco smoking were less tolerant of the school indoor environment. Dissatisfaction also was increased among those dissatisfied with their psychosocial work climate. In older school buildings and buildings with displacement ventilation, there was less dissatisfaction with the IAQ.

Smedje, Norback, and Edling did not find a significant relationship between the complaints and the rate of air exchange or the CO_2 concentration. The CO_2 levels ranged from 375 to 2800 ppm. The air quality was perceived to be worse at higher exposure levels of airborne contaminants, such as VOCs (which ranged between 3 and 580 $\mu g/m^3$), molds (ranging between 7 and $360 \times 10^3/m^3$ for total molds), bacteria (ranging between 8 and $290 \times 10^3/m^3$ for total bacteria), NO_2 (ranging between 1 and 11 $\mu g/m^3$), CO (ranging between <0.1 and 0.9 $\mu g/m^3$), and respirable dust (ranging between 6 and 60 $\mu g/m^3$). Therefore, they concluded that exposure to indoor pollutants affects the perception of IAQ, even at the low pollutant concentrations normally found indoors. The relative humidity in these schools ranged between 16% and 75% with a mean of 38%.

Walinder et al. (1997) studied the potential for exposure to increased levels of indoor air pollutants in schools to increase swelling of the nasal mucosa. The degree of mucosal swelling was estimated indirectly via the decongestive effect of xylometazolin, measured with acoustic rhinometry. The study was conducted in 39 Swedish schools and included both children and adult staff. Walinder et al. found that the indoor concentrations of VOCs, respirable dust, bacteria, molds, and microbial VOCs (MVOCs) were highest (2–8 times higher) in the school that had the lowest ventilation rate and was naturally ventilated. They concluded that inadequate outdoor air supply in schools may lead to increased levels of indoor air pollutants, resulting in subclinical swelling of the nasal mucosa.

The relationship of asthma to the indoor environment and the occurrence of asthma among school employees was studied by Smedje et al. (1996). Data were gathered among Swedish school employees (1410 subjects) via questionnaire. Data on exposure were collected by monitoring temperature, relative humidity, rate of air exchange, CO_2, NO_2, formaldehyde, VOCs, MVOCs, respirable dust, molds, bacteria, allergens, and endotoxins in dust. The MVOCs identified were 3-methylfuran, 3-methyl-1-butanol, 2-methyl-2-butanol, 2-pentanol, 2-heptanone, 3-octanone, 3-octanol, 1-octen-3-ol, 2-octen-1-ol, 2-methylisoborneol, geosmin, and 2-isopropyl-3-methoxypyrazine. No significant correlation was found between asthma and air exchange rate, type of ventilation system, visible dampness, amount of fabrics or open shelves in the classroom, room temperature, relative humidity, CO_2, respirable dust, viable or total bacteria, viable molds, total MVOCs, formaldehyde, total VOCs, NO_2, cat or dog allergens, or endotoxins. Significance was more common among atopic individuals, those who had recently painted in their homes, and those who felt work was stressful.

Asthma was found to be more common among subjects working in schools with higher concentrations of total molds and four MVOCs: 3-methylfuran, 2-heptanone, 1-octen-3-ol, or 2-methylisoborneol. The concentrations found of these MVOCs were very low. Smedje et al. concluded that the relationship to asthma may be principally that the occurrence of MVOCs in indoor air is an indicator of active microorganism growth compared with measurements of airborne microorganisms. MVOCs also have the advantage of providing data about microbial growth inside sealed surfaces. The authors emphasized that these results stress the importance of building, controlling, maintaining, and cleaning schools so that exposure to microbial growth is limited. ❖

4 ❖ FACTORS DETERMINING GROWTH OF MICROORGANISMS

In buildings, the conditions for microbial growth vary from structures where water is scarce or seldom available to those where water is constantly present. Systems containing water, such as standing water in cooling coil drain pans or condensed water on cold surfaces (i.e., slab floors, inner walls, or ductwork), favor the growth of bacteria, algae, protozoa, and certain fungi. Consistently high numbers of bacteria in office buildings (excluding food service areas) have been associated mostly with standing water. Most fungi, however, prefer the surfaces of moist materials instead of liquid water (Nevalainen 1993). Buildings that have suffered water damage from leakage or flooding often experience fungal “blooms” that may degrade air quality (Morey 1992). The inside surfaces of outside walls or any surfaces that are temperature clines (wide and/or rapid fluctuations) and foci of condensation may support microbial growth (Flannigan 1992).

In the past few years, fungi have been increasingly linked to SBS (Miller 1992; Samson et al. 1994). The sources and sites of amplification of fungi in indoor environments are highly variable; as a result, establishing a direct link between the presence of fungi and SBS is often problematic. In individual residences, in older buildings with water damage and decay, and in situations following chronic or catastrophic water damage, the harmful effects of fungi are more obvious (Batterman and Burge 1996; Samson et al. 1994, p. 695).

Fungi have been increasingly linked to SBS in recent years. A number of construction materials support their growth, particularly if those materials are wet and dirty.

Typical construction materials that can support the growth of fungi include wood, cellulose, hemicellulose, and wallpaper; some organic insulation materials; glues, paints, and mortars that contain carbohydrates or proteins; and textiles, especially natural fibers. Materials that are not easily degraded by fungi—such as mineral wool, metal, polyvinyl chloride and other synthetic polymers, and bricks, tiles, and other such mineral products—still may be extensively colonized by fungi (Ahearn et al. 1995, 1996). In such cases, the fungi do not use the metal or concrete for their growth but, rather, use the water and organic debris on the surface, including organics absorbed from the air (Nevalainen 1993; Ahearn et al. 1996). Fungi that have been isolated commonly from indoor environments include species of *Aspergillus, Penicillium, Cladosporium, Alternaria* and *Aureobasidium* species (Bisett 1987; Nelson et al. 1988; Ahearn et al. 1991; Mishra et al. 1992; Ahearn et al. 1992a; and Nevalainen 1993). These fungi usually are recovered from sources such as wood rot in domestic interiors, wall coverings, house dust, pets, and houseplants (Mishra et al. 1992; Ahearn et al. 1992b).

Growth of Fungi in HVAC Systems

HVAC systems have been associated with increased airborne densities of fungi of various genera, particularly *Cladosporium* and *Penicillium* (Hirsch, Hirsch, and Kalbfleisch 1978; Mishra et al. 1992). Ahearn et al. (1991) reported the colonization of painted metal surfaces of HVAC systems by *Cladosporium* sp. in a study in which airborne conidia appeared in low densities. The fungi were present not in the form of dormant conidia originating from outside air, but as reproducing fungal colonies tightly adhered to the metal surfaces. In Belgium, studies of air-conditioned buildings suggested that the HVAC system was the source of *Penicillium* sp. in the indoor air (Heinemann, Beguin, and Nolard 1994).

Many species of fungi have been isolated from various types of fiberglass used in HVAC systems, particularly when the fiberglass was laden with soil and moisture (Morey 1992; Morey 1993; Bjurman 1993). Ahearn et al. (1992a, 1996) reported the colonization of relatively new fiberglass duct insulation in well-maintained HVAC systems. The facings of the duct insulation were densely colonized with a few species of xerophilic fungi (*Talaromyces* sp. and *Eurotium herbariorum*) or *Penicillium* sp. and *Cladosporium* sp. Colonization appeared related to the use of adsorbed organics and the availability of moisture. Price et al. (1994) and Ezeonu et al. (1994), in laboratory challenge studies, demonstrated that certain types of new fiberglass insulation were readily colonized by certain species of fungi (e.g., *Aspergillus versicolor*) with resistance to formaldehyde residues as a probable selection factor.

Armstrong Laboratory (1992) reports that its studies showed complaints of musty odors and allergic or asthmatic reactions were confined to microbiologically contaminated buildings. The causes of bioaerosol contamination were (1) poorly maintained HVAC systems, (2) high space relative humidities, (3) water-soaked materials, such as ceiling tiles, walls, and carpets, and (4) sick occupants transmitting viruses in the highly recirculated air systems. The most common health complaint from bioaerosol contamination was allergic reactions leading to hypersensitivity pheumonitis, allergic rhinitis, and allergic asthma. Most often, these symptoms were caused by mold spores or bacteria that had accumulated in the ventilation systems. For microbiological contamination to occur, three conditions must be met: (1) the organism must be able to enter the ventilation system, (2) there must be an amplification site promoting growth to problem levels, and (3) dissemination must occur. The Armstrong report states that the normal indoor mold levels average 60 cfu/m^3, and normal bacteria levels average 80–100 cfu/m^3. It recommends that indoor mold concentrations in excess of 200 cfu/m^3 be considered to signify unacceptable contamination.

Toxin Production by Fungi

Mycotoxins are secondary metabolites that are produced by strains of some species of fungi under restrictive environmental conditions, usually during the stationary growth phase. Although the vast majority of mycotoxin studies have involved foods, some intoxications [e.g., “atypical farmers lung,” studied by Emanuel, Wenzel, and Lawton (1975)] appear to involve inhalation of mycotoxin-containing dust and/or spores (Jarvis 1990).

Some fungi commonly found indoors—for example *Aspergillus versicolor, A. parasiticus, A. flavus, Penicillium* spp., *Fusarium* spp., *Trichoderma* spp. and *Stachybotrys (atra) chartarum*—may produce a variety of toxins that might become airborne (Smith and Hacking 1983; Bisett 1987; Sorenson et al. 1987; Jarvis 1990; Borgesson, Stollman, and Schnurer 1992; Mattheis 1992; Johanning, Morey, and Goldberg 1993). *Stachybotrys chartarum* is the etiologic agent of stachybotryotoxicosis and has been found to produce a potent cytotoxin, satratoxin H (Bisett 1987; Johanning, Morey, and Goldberg 1993). This toxin is a member of the tricothecene mycotoxin group and is the most active of these mycotoxins (Johanning, Morey, and Goldberg 1993). Trichothecenes produced by *Stachybotrys chartarum* and *Trichoderma* spp. are potent inhibitors of protein synthesis. Toxic effects include dermatitis, respiratory irritation and distress, cardiovascular effects including lowered blood pressure, and immunosuppressive effects (Bisett 1987; Johanning, Morey, and Goldberg 1993). The intestinal tract is also an important target organ, and acute poisoning may lead to severe nausea and diarrhea (Johanning, Morey, and Goldberg 1993). Some of these symptoms were reported for inhabitants of a building found to be significantly contaminated by *Stachybotrys chartarum* (Croft, Jarvis, and Yatawara 1986). Sorenson et al. (1987) later confirmed the presence of trichothecene toxins within the conidia of *Stachybotrys chartarum*.

A review of two buildings reported by Morey (1992) showed that several occupants in one building had developed asthma or allergic respiratory illness that appeared to be building-related. Air and surface sampling in the building revealed high concentrations of *Aspergillus versicolor* (>20,000 colony-forming units/m^3) in the air, as well as *A. versicolor* and *Stachybotrys chartarum* on some contaminated walls. Because conidia of these species potentially contain sterigmatocystin, prolonged exposure to and inhalation of high numbers may present a health hazard (Bisett 1987; Jarvis 1990; Morey 1992; Johanning, Morey, and Goldberg 1993). Our experiences with buildings colonized by both these species have shown them to have an anecdotal association with abnormally high incidences of malaise and absenteeism among occupants. Where toxigenic fungi such as *Aspergillus flavus* or *Stachybotrys (atra) chartarum* are concerned, toxicoses as well as allergenic responses require consideration. The conditions for toxin production appear to be restricted in most cases, and the presence of a potentially toxigenic fungus does not necessarily indicate the presence of the toxin as well.

Production of Volatile Emissions by Fungi

A number of fungi are known to produce volatile metabolites on natural substrates. Borgesson, Stollman, and Schnurer (1992) studied the growth of six fungi— *Aspergillus candidus, A. flavus, A. versicolor, Penicillium brevicompactum, P. glabrum*, and *P. roqueforti*—on oat and wheat meals. They found that all species produced a variety of volatile metabolites and that all species produced 3-methyl-furan regardless of substrate. Aliphatic alcohols, ketones, and terpenes appear to be the predominant volatiles produced by fungi; as many as 50 volatile compounds have been identified from *Aspergillus clavatus* alone (Bisett 1987; Borgesson, Stollman, and Schnurer 1990; Bjurman and Kristensson 1992a; Bayer and Crow 1993). Some of the more commonly identified VOCs of fungi include geosmin, 3-octanone, 2-octen-1-ol, 3-methyl-1-butanol and 3-methylfuran (Bisett 1987; Borgesson, Stollman, and Schnurer 1992; Mattheis 1992; Bjurman and Kristensson 1992b; Zeringue, Bhatnagar, and Cleveland 1993). The types of volatiles produced are greatly influenced by the type of medium or substrate on which the fungus is growing (Bjurman and Kristensson 1992; Bjurman 1993; Nikulin et al. 1993).

Fungi and actinomycetes have been shown to produce a range of VOCs, including many compounds such as acetone, ethanol, and isopropanol, more commonly associated with solvents and cleaning materials (Bayer and Crow 1993). Bayer and Crow demonstrated that a range of fungi isolated from indoor environments are capable of producing and emitting these compounds into the atmosphere when grown on complex media. At least 26 different

Fungi and actinomycetes produce a range of VOCs, including many compounds commonly associated with solvents and cleaning materials.

volatile compounds were found to be produced by the fungi in this study, including known carcinogens such as benzene.

Strom et al. (1994) investigated the production of MVOCs as a means to detect the occurrence of fungi and bacteria within building constructions. A significant increase in the concentration of MVOCs was observed in houses with microbial odor problems, compared with unaffected houses and outdoor air samples. Microbial analysis of damaged building materials from houses with odor problems showed highly significant differences from the corresponding material collected from unaffected houses. Additionally, it was found that MVOCs diffuse through plastic sheeting used as water vapor barriers. Therefore, these barriers do not prevent the diffusion of the MVOCs and permit contamination of the indoor air with microbial odors.

Strom et al. identified the representative MVOC compounds that indicate microbial activity to be 3-methylfuran, 2-methyl-1-propanol, 1-butanol, 3-methyl-1-butanol, 3-methyl-2-butanol, 2-pentanol, 2-hexanone, 2-heptanone, 3-octanone, 3-octanol, 1-octen-3-ol, 2-octen-1-ol, 2-methylisoborneol, geosmin, and 2-isopropyl-3-methoxypyrazine. The primary odor-causing compounds are probably geosmin, 2-methylisoborneol, and 2-isopropyl-3-methoxypyrazine. These three compounds have an “earthy” odor. A mushroom-like odor is produced by 1-octen-3-ol and 2-octen-1-ol. These are thought to be the source of the “musty” odor.

Ezeonu et al. (1994) demonstrated the production of 2-ethyl hexanol, cyclohexane, and benzene by a mixed fungal population colonizing fiberglass insulation. *Aspergillus versicolor* and *Chaetomium globosum* have both been shown to produce geosmin, a VOC with a distinct “earthy” odor (Bjurman and Kristensson 1992a, b). Geosmin has also been associated with *Streptomyces* sp. isolated along with a number of fungal species from an odor-producing HVAC system (Crow 1993). Moisture requirements for volatile production by fungi also may be different from those for growth (Moss 1991; Bjurman and Kristensson 1992a; Nikulin et al. 1993). The possibility exists that VOCs produced by fungi at one location in a structure could influence the growth of other fungi at remote sites through dissemination of these compounds by mechanical ventilation systems. This influence could indirectly contribute to further degradation of air quality as a result of increased airborne loading of conidia, sclerotia, or hyphal fragments.

Horner, Morey, and Worthan (1997) performed sampling in an extensively water-damaged school. The students and teachers were complaining of musty odors and allergic responses. *Cladosporium cladosporidoides* dominated all of the outdoor air samples and was collected in 99% of the indoor air samples. The total concentrations of the culturable molds were lower indoors than outdoors when the ventilation system was operating, indicating that airborne exposure to the fungi indoors was similar to the outdoor exposure. However, dust sampling of the carpet, air supply louvers, and duct liner surfaces indicated microbial amplification. MVOCs were also measured, and 2-octen-1-ol was detectable at most of the sampling locations. MVOCs were not detectable in the noncomplaint or outside samples.

Joki et al. (1993) found that the respiratory symptoms of people living in moldy houses may be caused by MVOCs. These researchers studied the effects of MVOCs from *Penicillium*, *Trichoderma viridae* and two actinomycete strains, along with those from *Klebsiella pneumoniae* lipopolysaccharide on tracheal tissue in vitro. *Trichoderma viridae, Penicillium*, and the actinomycete strains showed a tendency towards ciliostimulation. The effect was similar to the ciliostimulatory effect brought about by respiratory infections. Joki et al. concluded that the MVOCs could adversely affect the mucociliary defense in respiratory airways. ❖

5 ❖ HUMIDITY CONTROL AND THE IMPACT ON IAQ

Impact of High Space Humidity

As discussed previously, moisture is a key factor in the growth and amplification of mold, fungi and other microbes. As a result, problems with these organisms can be severe in air-conditioned buildings located in humid environments, especially the southern United States and tropical climes. The accumulation of moisture on or in the envelope of buildings in these climates is strongly influenced by indoor temperature and outdoor humidity. Mold growth typically occurs on internal surfaces of the external walls or floors, since these surfaces are cooled by the air-conditioning system to below or near the dew point temperature of humid air infiltrating into the building envelope (Flannigan and Morey 1996). Moisture enters the building because of (1) leakage of rain into the wall cavities, (2) movement of humid air into the interior because of poor building construction, (3) water vapor diffusion from the humid exterior to the dry interior, and, perhaps most common, (4) entry through the conventional HVAC system when the supply air fan is operated while the cooling coil is cycled off.

Overcooling of indoor spaces results in moisture and mold problems in buildings in climates where the outdoor dew point temperature is at or above about 25°C (77°F). The problems can become severe when the internal surface temperatures drop a few degrees below 25°C and the likelihood increases that the surface relative humidity will exceed 65% (Flannigan and Morey 1996). Ironically, when building occupants feel clammy because of high space humidity, the typical response is to lower the space thermostat setting. The result is that the space cools further, most often increasing the space relative humidity along with the likelihood of condensation of moisture on supply air ducts, floors, and other building surfaces.

Moisture is a key factor in the germination of mold, fungi, and other microbes; and therefore, problems with these organisms can be severe in air-conditioned buildings in humid climates because of overcooling of indoor spaces.

Moisture problems can also be a function of the occupancy load (Merrill and TenWolde 1989). High occupant densities, such as those in schools, generally result in a relatively high degree of moisture release into room air. When there is a combination of high occupant densities (such as in schools), poor ventilation, and cold external walls, often moisture, dirt accumulation, and mold growth occurs in walls and on building surfaces. These can be controlled by proper ventilation with preconditioned (dehumidified air at room neutral temperature) outdoor air (Lstiburek 1994).

Fischer (1996) concluded that improved humidity control, reduced coil condensate, and the low (60%) relative humidity maintained in the supply air ductwork by a DWERS helps to avoid microbial problems and illness in humid climates. Fischer based his conclusions on a survey of eight schools investigated. The schools were specifically chosen because each had experienced serious IAQ problems, had subsequently been retrofitted with desiccant-based total energy recovery systems, and had since operated with these systems for at least 2 years. His survey revealed that in each of the schools, the modifications resulted in a complete and lasting resolution of the IAQ problems.

In eight schools studied by Fischer, improved humidity control, reduced coil condensate, and the low relative humidity maintained by a DWERS helped avoid microbial problems and illness.

Baughman and Arens (1996) summarize numerous health-related effects associated with high and low indoor relative humidity, including mycotoxins and VOCs produced by fungi. Bayer, Crow, and Noble (1995) investigated schools with complaints of rashes and respiratory illnesses. The investigation focused on microbial growth, which was identified in all cases. It concluded that many of the airborne VOCs appeared to be microbial in origin. Bayer and Downing (1992) reported on three schools using packaged HVAC equipment that were investigated and found to have serious humidity problems, even with only small percentages of intermittent outdoor air supplied to the occupied space.

The Armstrong Laboratory (1992) study cited microbial contamination in nearly 50% of the buildings investigated. Its authors stated that, based on their findings, carpet, curtains, furniture, and so on can absorb enough moisture at space humidities greater than 65% to promote microbial growth. At relative humidities greater than 70%, according to the report, VOCs are emitted at greater rates than at below 60%. The Armstrong report recommends that buildings be operated to maintain the space relative humidity between 40 and 60%. This study agrees well with ASHRAE Standard 62-1989, which recommends that space relative humidity be maintained at between 30% and 60%.

Impact of Low Space Humidity

The Armstrong Laboratory (1992) report states that relative humidities of less than 40% cause physiological effects leading to environmental discomfort and dissatisfaction. The symptoms include dry and sore nose and throat, bleeding nose, sinus and tracheal irritation, dry scratchy eyes, inability to wear contact lenses, and dry, itchy, flaky skin. Low relative humidities contribute to an increase in respiratory illness by weakening the defense provided by the mucous membranes. This report recommends that relative humidity be controlled between 40 and 60%, and that humidity control devices be installed in the HVAC systems because "natural" humidification does not maintain the relative humidity of a building at 40 to 60% throughout the entire year.

A study conducted by Arundel et al. (1986) concluded that influenza virus cultivated in human cells survived at the highest rate when exposed to low relative humidities (20%), survived at a minimum rate at between 40% and 60% RH, and increased again after exposure to high humidity (70–80%). A plot of the morbidity from colds and low indoor humidity has been shown by Hope-Simpson (1958) to have a "high correlation."

Three different researchers studied the relationship between humidification and absenteeism (Sale 1972; Ritzel 1996; Green 1974, 1985). Sale and Ritzel studied controlled populations of kindergartens to determine the relationship between respiratory illness and space relative humidity. Both studies found that in schools where the humidity was increased with humidifiers, the absenteeism was 40 to 50% lower than in unhumidified schools. They reported a decrease in colds, sneezing, sore throats, and fever experienced by the children in spaces humidified in winter. Sale included approximately 500 kindergarten children in the study, investigating the impact of humidification in the home in conjunction with humidification in the school. The students were divided into four groups (the rate of absenteeism is in parentheses): humidification at home and at school (1.3%), humidification at school only (3.9%), humidification at home only (5.1%), and no humidification (7.1%).

Green (1974) compared the absenteeism in 18 schools, with a total of approximately 4800 students, for 11 years. Some of the schools were humidified to greater than 25% and others were not humidified. There was a statistically lower rate of absenteeism in the humidified schools. He concluded that a possible reason for the reduction in absenteeism may have been a reduction in disease transmission.

Fischer (1996) concluded that the free humidification provided by total energy recovery systems can maintain the space relative humidity above 30% during all but the most extreme winter time conditions, and can thereby reduce the incidence of respiratory illness and absenteeism in classrooms located in colder climates. ❖

6 ❖ VOCs AND OTHER CHEMICAL COMPOUNDS THAT AFFECT IAQ

Downing and Bayer (1993) investigated the relationship between ventilation rate and IAQ in classrooms. Their investigation was conducted in a 2-year-old school in Georgia that has experienced serious IAQ problems and SBS. Samples were collected and analyzed for VOCs, formaldehyde, CO_2, temperature, and humidity. Downing confirmed in this study that 15 cfm of outdoor air per student, provided continuously, was required to maintain CO_2 concentrations at levels below 1000 ppm. The recommendation is made that classrooms, both new and existing, be provided with at least 15 cfm per student of outdoor air on a continuous basis during school hours. It was found that VOC concentrations exceeded 1000 $\mu g/m^3$ when only 5 cfm per student was provided, even on a continuous basis, and that the occupants were dissatisfied with the air quality at these conditions. Tucker (1986) indicated that this level of VOCs is an indication of potential IAQ problems. Hydrocarbon levels measured in the classroom were found to be nine times higher than those measured outdoors when the outdoor air quantities were cycled with the cooling coil. Indoor hydrocarbon levels were reduced to approximately the outdoor concentration levels when 15 cfm of outdoor air per student was provided on a continuous basis and humidity was controlled.

The school investigated by this study used 3-ton rooftop-packaged systems operating at a maximum of 5 cfm per student. The relative humidity exceeded 70% for extended time periods (see Fig. 1), resulting in microbial amplification. With the original HVAC system in operation, there was visible mold growth on building surfaces, ceiling tiles, and books. The IAQ complaints and illnesses included respiratory and allergy problems, headaches, and lethargy. When the HVAC system was modified to include a DWERS that provided a continuous outdoor air supply of 15 cfm per student and controlled the space relative humidity

In a Georgia school, when the HVAC system was modified to include a DWERS that provided a continuous outdoor air supply of 15 cfm per student and controlled the space relative humidity at between 50 and 55%, all complaints related to IAQ — respiratory and allergy problems, headaches, and lethargy — ceased.

at between 50 and 55%, all complaints regarding IAQ stopped. They have not returned after approximately 5 years of operation.

As discussed previously, Bayer and Crow (1993); Borgesson, Stollman, and Schnurer (1992); Bjurman and Kristensson (1992b); Nikulin et al. (1993); Strom et al. (1994); and others documented the emission of a wide range of VOCs and mycotoxins associated with microbial activity in buildings. These emissions have been documented in both dry climates (i.e., Sweden) and humid climates. As shown in the Downing and Bayer (1993) investigation, the measurement of specific VOCs can serve as an effective marker for identifying microbial activity. According to this investigation, continuous ventilation may have served to purge the high levels of VOCs resulting from microbial activity, as well as limit the possibility that VOCs produced by fungi at one location would enhance the growth of other fungi at other sites throughout the facility.

Clark (1996) suggests that a CO_2 level of 1000 ppm (the suggested maximum indoor air guideline limit for CO_2 in ASHRAE Standard 62-1989) may be too high, based on data reported in the medical literature. He reports that 15 minutes of exposure to 1200 ppm of CO_2 results in nausea, claustrophobia, headaches, “stuffy” feelings, shortness of breath, and deep breathing. Long-term exposure to 1200 ppm of CO_2 results in upper-limit tolerance and calcium deposition in body tissues. This level of CO_2 will often be reached in school classrooms with 15 cfm per person of fresh supply air. In school classrooms with 5 cfm per person of fresh supply air, the level of CO_2 is 2500 ppm; higher levels of CO_2 in a classroom will deplete the amount of available O_2, causing symptoms of oxygen deprivation among the children. Clark notes that schools have high population densities and marginal air quality and are therefore good areas for research into the actual amount of fresh supply air required to lower the CO_2 levels to an acceptable level. The acceptable level may be as low as 600 ppm, the maximum allowable long-term exposure level allowed on U.S. Navy submarines. In Clark’s opinion, research is needed to examine the possibility that the CO_2 levels found in schools are causing the increased incidence of disabling emotional and learning disorders among school children.

In one researcher’s opinion, studies are needed to determine whether CO_2 levels found in schools are causing the increased incidence of emotional and learning disorders among children. Another group of researchers found that CO_2 concentrations in excess of 600 ppm cause significant physiological effects, such as fatigue, drowsiness, lack of concentration, and sensations of breathing difficulty.

The Armstrong Laboratory (1992) report concludes that CO_2 concentrations in excess of 600 ppm cause significant physiological effects, such as fatigue, drowsiness, lack of concentration, and sensations of breathing difficulty. These researchers state that they found between 15 and 33% of the population will have symptoms from CO_2 exposure at 600–800 ppm, 33 to 50% will have symptoms at 800–1000 ppm, and 100% will show symptoms at greater than or equal to 1500 ppm. This report claims that humans will experience an increase in breathing rate just from a slight change in CO_2 level above the normal ambient CO_2 level of 300–400 ppm. Based on these findings, this report recommends that CO_2 concentrations not exceed 600 ppm, a level that can be achieved with a minimum of 40 cfm per person. If the CO_2 concentration exceeds 600 ppm, complaints of drowsiness, fatigue, difficulty in concentrating, and difficulty in breathing can be expected.

Bakke and Levy (1990) investigated the IAQ in six kindergartens during the winter in Norway. He found a correlation between the highest CO_2 levels and highest relative humidity and the most frequent complaints of “dry air” and eye irritation (which is usually associated with dry air). The complaints of dry air were most frequent at the kindergartens with the lowest ventilation rate and the highest relative humidity. Bakke concludes that high CO_2 levels and high relative humidity may indicate that a building has a ventilation rate that is too low. ❖

7 ❖ CONTROL OF INDOOR ENVIRONMENTS WITH HVAC SYSTEMS

The quantity of air in a modern building is highly dependent upon the operation of its HVAC system. HVAC systems are designed to mix a given amount of outdoor air with some amount of recirculated air, condition this mixture, and distribute it to the occupied space (Morey 1988). The amount of recirculated air in the mixture varies from system to system and building type to building type.

Large buildings typically use chilled water systems with large central air handling systems that, if sized correctly, are capable of conditioning the outdoor air quantities recommended by ASHRAE Standard 62-1989. A conventional variable-air-volume (VAV) system distributes approximately 1.5 cfm/ft^2 of 56° air, of which typically 20% is outdoor air and 80% is recirculated air. However, it has been shown that even if 15 cfm per person of outdoor air is provided to the central air handling system, it is possible to have poor air circulation within individual zones. The lack of circulation causes contaminant buildup either continuously or intermittently at low-flow (part-load conditions) within a typical VAV system (Meckler 1992). For this reason, ASHRAE recommends increasing the outdoor air quantity delivered to the VAV system beyond 15–20 cfm per person (Z factor) to ensure adequate outdoor air to all zones (Brady 1996).

In large buildings, an HVAC system may serve to transport microorganisms from the locus of contamination (e.g., a humidifier or moist insulation) to the vicinity of sensitive occupants (Morey 1988; West and Henson 1989; Morey 1992; Price et al. 1995; Batterman and Burge 1996). For this and other reasons discussed previously, both outdoor air ventilation and humidity control are essential issues in the relationship between HVAC systems and IAQ.

Innovative designs have been employed in large buildings to ensure adequate humidity control and outdoor air delivery with traditional VAV systems. For example, a cold air distribution system can be applied so that all of the air processed by the VAV air handling system is outdoor air (Meckler 1992).

The use of innovative HVAC designs in large buildings can ensure adequate humidity control and outdoor air delivery with traditional VAV systems.

Bayer and Downing (1991) investigated a 30-story building that successfully used a total energy recovery preconditioning unit to provide a constant supply of outdoor air to each VAV system on a floor-by-floor basis. This system ensured that approximately 20 cfm of outdoor air per person was delivered even as the return air percentage varied between 80 and 20% at the VAV air handling system. Various contaminants measured— including VOCs, CO_2, formaldehyde, and others— confirmed the effectiveness of this design approach.

The vast majority of facilities constructed each year in the United States are considered small buildings (i.e., three stories or less). These facilities—which include small offices, schools, restaurants, municipal buildings, and nursing homes—typically use packaged HVAC equipment because of its low cost, compact size, and ease of installation and maintenance. Unfortunately, packaged equipment is far more limiting with respect to outdoor air delivery and humidity control capability than are the large chilled water systems used in large buildings. Packaged systems have been designed to provide only a modest percentage of outdoor air on an intermittent basis in order to minimize cost. When they are operated with continuous outdoor air or an increased percentage of outdoor air, comfort and humidity control is often lost (Downing and Bayer 1993; Henderson and Rengarajan 1996).

As a result, small facilities often are not designed and/or operated in accordance with ASHRAE 62-1989. Besides the inability of packaged equipment to accommodate increased outdoor air ventilation rates and maintain space comfort, reasons include the perception that there is a significant first-cost premium, potentially high operating costs, and a general ignorance of IAQ on the part of many building owners and installation contractors. Many small buildings are constructed on a design/build basis, with the installing contractor (not a consulting engineering firm) completing the mechanical design with the primary objective of minimizing the HVAC system installation cost.

Until recently, few economical options have been available to design engineers and contractors that combine effectively with conventional packaged HVAC equipment and enable it to perform as required while accommodating the recommendations made by ASHRAE 62-1989 (i.e., increased outdoor air provided on a continuous basis to the occupied space). As a result of these and other factors, many small buildings have been designed with an inadequate supply of outdoor air being provided on an intermittent basis. Two of the most common design schemes are the following:

- Using rooftop packaged equipment that provides approximately 10 to 15% outdoor air. In very cold or hot/humid climates, the fans in these units are typically cycled with the heating source (burner) or cooling source (coil), to avoid dumping of cold air during the heating mode and poor humidity control during the cooling mode.

- Using rooftop packaged equipment or split systems with little or no outdoor air being provided to the space by the HVAC equipment. Infiltration through door and building leaks is assumed to deliver “adequate” outdoor air.

As the research summarized in this paper indicates, compromising either the continuous supply of outdoor air or proper humidity control can result in serious IAQ problems, especially in school facilities. During the air-conditioning season, the intermittent use of ventilation causes extreme variation in indoor contaminant concentrations and space relative humidity, which may result in absorption of water into porous materials (West and Henson 1989; Morey and Williams 1991). The availability of both water and nutrients controls microbial growth in porous insulation. Water condensation alone is not a problem as such, but if the temperature is sufficient and organic material is present, viable fungal spores will have an opportunity to germinate and proliferate (Morey and Williams 1991).

Fischer (1996) concluded that desiccant-based recovery systems can be easily and cost-effectively integrated with conventional packaged HVAC equipment to provide the increased outdoor air quantities and humidity control recommended by ASHRAE 62-1989 and shown to be critical by the research summarized in this paper. In his investigation, Fischer summarizes first-cost information provided by the design engineers for seven different school projects which demonstrates that the ASHRAE 62-1989 recommendations can be accommodated with a cost-effective mechanical design. In each project, the benefits of improved IAQ were found to far outweigh any incremental investment by the engineers, owners, and occupants required to incorporate the required desiccant-based preconditioning equipment.

Desiccant-based energy recovery systems, dehumidification, and cooling systems and various other overcooling with reheat approaches can dehumidify the outdoor air stream provided to the occupied space or to the intake of the conventional HVAC equipment. Thus, downsized packaged equipment linked with a preconditioning system can be cost-effective means of accommodating the ventilation and humidity control needs recommended by ASHRAE.

Investigations by Bayer and Downing (1991), Coad (1995), and Downing and Bayer (1993) all support the need to improve the performance of packaged HVAC equipment through preconditioning the outdoor air supplied to a building so that the latent load (humidity) is decoupled from the sensible (temperature) load that is effectively handled by the packaged HVAC equipment. The sensible load can then be easily managed, usually with smaller-capacity packaged equipment, using simple thermostat controls and on a room-by-room basis if desired. Such an arrangement provides improved comfort and energy efficiency and is probably the most cost-effective way of accommodating the ASHRAE 62-1989 guidelines.

Numerous articles and manufacturer case histories are available to demonstrate how technologies such as desiccant-based energy recovery, dehumidification, and cooling systems and various other overcooling with reheat approaches have been applied successfully to dehumidify the outdoor air stream provided directly to the occupied space or to the intake of the conventional HVAC equipment (HPAC 1996a, 1997; Gatley 1993; Turner et al. 1996). These approaches have shown that downsized packaged equipment linked with a preconditioning system can be cost-effective to install and operate and can accommodate the ventilation and humidity control needs recommended by ASHRAE. In addition, some of the desiccant system design approaches have been shown to deliver air through the ductwork that is well below saturated conditions, operate with dry cooling coils, remove contaminants from the outdoor air and kill bacteria, all of which are beneficial to improving indoor environments.

An alternative approach was used by one engineering firm in a south Florida high school (HPAC 1996b). The school board requested that the outside air flow rate be lessened to 5 cfm per person so that the operating costs and humidity control needs would be reduced. The problem with this approach, as was recognized by the engineering firm, was that lessening the amount of fresh ventilation air probably would lead to costly maintenance and operations problems, and to occupant health and comfort problems. The engineering firm chose to use increased filtration, rather than innovative ventilation technology, applying the Indoor Air Quality Procedure in ASHRAE Standard 62-1989. Eighty-five percent efficiency particle filters and 80% carbon-absorbing gaseous removal filters were installed. The suppliers of the filters were required to provide written documentation that the filtration devices would provide the equivalent IAQ that would be achievable with increased quantities of outside air, documenting compliance with ASHRAE 62-1989. The report does not present longitudinal air testing data in the school to prove the maintenance of adequate indoor air quality in the school. ❖

8 ❖ IMPACT OF IAQ ON PRODUCTIVITY AND SATISFACTION IN THE LEARNING ENVIRONMENT

Even though IAQ is perceived to be important for the learning ability of students (Clark 1996; Daisey and Angell 1998), there have been few good scientific, statistically sound studies of school IAQ and its impact on the learning ability of students. Romm (1994) and Romm and Browning (1994) documented that buildings and offices that were designed or renovated to reduce energy use and indoor pollution boosted worker efficiency by increasing output, decreasing errors, and improving attendance. Romm looked for a similar result in schools but found that there are virtually no environmentally sustainable schools and few studies on the productivity consequences of energy-saving measures in educational facilities. McLoughlin et al. (1983) conducted a series of studies to clarify the relationship between allergies and school performance and behavior. Although he was not able to demonstrate a direct link between allergy and allergy treatment and academic performance, he was able to show that there was a relationship between respiratory problems and listening and attention. He found that eustachian tube disfunctions were related significantly to academic performance and behavior. There are, however, studies linking specific environmental conditions, such as light, noise, or room color, to student performance (Lytton 1997). These studies provide anecdotal evidence that healthful and well-lit schools may result in higher academic achievement. However, the complexity of measuring academic performance and understanding how it is achieved challenges claims of direct causal links.

Three different researchers studied the relationship between humidification and absenteeism (Sale 1972; Ritzel 1996; Green 1974, 1985). Sale and Ritzel studied controlled populations of kindergarteners to determine the relationship between respiratory illness and space relative humidity. In both studies, in the schools where the humidity was increased with humidifiers, absenteeism was 40% to 50% lower than in unhumidified schools. The schools reported a decrease in colds, sneezing, sore throats, and fever experienced by the children in spaces humidified in winter. Sale included approximately 500 kindergarten children in the study, investigating the impact of humidification in the home in conjunction with humidification in the school. The students were divided into four groups (rate of absenteeism in parentheses): humidification at home and at school (1.3%), humidification at school only (3.9%), humidification at home only (5.1%), and no humidification (7.1%).

Green compared the absenteeism in 18 schools, a total of about 4800 students, for 11 years. Part of the schools were humidified to greater than 25%, and others were not humidified. There was a statistically lower rate of absenteeism in the humidified schools. He concluded that a possible reason for the reduction in absenteeism may have been a reduction in disease transmission.

Fischer (1996) compared the actual cost premium associated with accommodating ASHRAE Standard 62-1989 recommendations in school facilities with the costs for the same facility designed to provide only 5 cfm per student of outdoor air without controlling the indoor relative humidity between 60 and 30%. This investigation concluded that cost premiums associated with compliance with ASHRAE 62-1989 recommendations ranged from $62 to $205 per student, and averaged $95 and $142 for the single-wheel total energy recovery system (TERS) and the dual-wheel desiccant-based total energy recovery system (DWERS) approaches, respectively (Table 1). Fischer concluded that the cost savings and cost avoidance associated with the benefits likely to be recognized from providing a desirable IAQ in the school environment would justify this additional expenditure.

Fischer also surveyed school operators to quantify legitimate cost savings and cost avoidance numbers (see Table 1) to support the conclusion that the payback period associated with providing a desirable IAQ may be very short. He reported that many of the benefits listed would be recognized year after year, whereas the cost associated with providing the desired IAQ is a one-time expense if energy recovery is used to offset the added energy requirements. The projected benefits—which included reductions in absenteeism, substitute teachers, and health care costs—quickly exceed the initial expense associated with the improved indoor environment.

Hardin, in personal communication, estimates the cost to the state of Washington for poor humidity control in schools in billions of dollars for structural damage alone. Schools are not the only structures with billions of dollars with structural damage due to poor humidity control in Washington State. Hardin also estimates that there are billions of dollars of damage to multifamily housing. ❖

Table 1. Cost vs benefit comparison for providing desirable IAQ in schools

Added costs for desirable IAQ	Benefits from maintaining desirable IAQ	
Case 1: Hot, humid climate[a] DWERS approach: $142/student[b] **Case 2:** Moderately humid/cold climate[c] TERS approach: $95/student[b]	• **Improved effectiveness of the learning process** Impacts on comprehension, alertness, drowsiness, allergies, respiratory illness	Significant $/ student
Notes *Abbreviations:* DWERS = dual-wheel desiccant-based total energy recovery system TERS = single-wheel total energy recovery system [a] Assumes the use of the dual-wheel, total energy recovery preconditioner directly to and from each occupied area, decoupling the outdoor air load from space load, which is handled by a typically 2-ton conventional HVAC. [b] Added cost reflects increase in overall mechanical cost of either the DWERS or TERS approach providing 15 cfm/person of outdoor air (as compared with only 5 cfm/person with a conventional HVAC) and continuously controlling space relative humidity. [c] Assumes the use of a single-wheel energy recovery preconditioner ducted to space or to the return air side of a conventional HVAC unit.	• **Reduced absenteeism** Funding increase based on reduced absenteeism	$57/student/year
	Savings due to fewer substitute teachers	$5/student/year
	Health care savings, reduced doctor visits	$107/student/year
	• **Avoided property damage** Carpet replacement in a typical school	$37/student
	Ceiling tile replacement in a typical school	$22/student
	Partial book replacement	$3/student
	• **Reduced maintenance costs** Doubled time between filter changes	$5/student/year
	• **Avoided remediation** Avoided duct cleaning, facility IAQ investigation, legal expenses	Significant $/ student

9 ❖ CONCLUSIONS

Based on this investigation it is clear that more research is justified to investigate the specific causes of IAQ problems within schools and to quantify the specific benefits that are recognized from providing a desirable indoor air environment. Given that the General Accounting Office concluded that one in five schools has IAQ problems, and given that thousands of schools are slated to be constructed or renovated within the next 5 years, the need to identify simple, effective, energy-efficient ways of resolving these IAQ problems is both obvious and significant.

Fortunately, as shown by this investigation, much credible research has already been conducted. Based on these scientific data, it can be concluded that most IAQ problems can be avoided (or resolved) by providing an adequate amount of outdoor air on a continuous basis, controlling space relative humidity so that it seldom exceeds approximately 60% or drops below approximately 30%, and using a level of outdoor air filtration efficiency necessary to prohibit most mold spores and fungi from entering the HVAC system.

The research conducted to date confirms that both proper outdoor air ventilation and humidity control are necessary. Too often in practice, one is obtained at the expense of the other. Packaged systems that provide the outdoor air volume only when the coil is energized improve humidity control but allow indoor contaminants to build to unacceptable levels. The same equipment can be operated with the supply fan running continuously and with an outdoor air damper adjusted to provide the required quantity of outdoor air, but humidity control is lost, especially at part-load conditions. Fortunately,

One in five schools has IAQ problems, and thousands of schools will be built in the next 5 years. How can we resolve these problems in existing schools and prevent them in new ones?

Most IAQ problems can be avoided or resolved by

- *providing an adequate amount of outdoor air on a continuous basis,*
- *controlling space relative humidity so that it seldom exceeds approximately 60% or drops below approximately 30%, and*
- *using a level of outdoor air filtration efficiency necessary to prohibit most mold spores and fungi from entering the HVAC system.*

proven and cost-effective system solutions exist that allow satisfaction of both the continuous ventilation and the humidity control objectives while they provide a central location for effective outdoor air filtration, which can be easily accessed for routine maintenance.

In summary, the research identified as part of this investigation provides the basis for the formation of a simple hypothesis: Most IAQ problems in school facilities can be avoided by (1) providing adequate outdoor air ventilation on a continuous basis (15 cfm per student), (2) controlling the space relative humidity between 30 and 60% and (3) providing effective particulate filtration of the outdoor air.

It is recommended that a research project be initiated to analyze a statistically significant number of existing school facilities, comparing those constructed with conventional HVAC system approaches that do not provide simultaneous, continuous ventilation and humidity control, with schools designed to include systems that meet the ventilation, humidity control, and filtration criteria in the previous paragraph. If our stated hypothesis is correct, the analysis we recommend should show very acceptable IAQ at the schools designed and operated to conform to ASHRAE Standard 62-1989 recommendations, and very few IAQ complaints by the occupants. Conversely, the schools that do not conform to the ASHRAE IAQ standard should show much higher levels of indoor air contamination and microbial activity and a much higher level of dissatisfaction with regard to IAQ among the occupants.

If the recommended research is completed, and assuming the stated hypothesis is confirmed, valuable direction would be provided to school officials, architects, and consulting engineers responsible for schools scheduled for construction or renovation in the future, as well as those faced with resolving the many IAQ problems that currently exist in school facilities. ❖

❖ REFERENCES

Ahearn, D. G., S. A. Crow, I. M. Ezeonu, et al. 1995. “Aspects of fungal growth in air distribution systems” pp. 395–405 in *Proceedings of Environmental Solutions to Indoor Air Quality Problems*, Air and Waste Management Association, Pittsburgh.

Ahearn, D. G., S. A. Crow, R. B. Simmons, et al. 1996. “Fungal colonization of fiberglass insulation in the air distribution system of a multi-story office building: VOC production and possible relationship to a sick building syndrome,” *J Ind Microbiol* **16:** 280–85.

Ahearn, D. G., D. L. Price, R. B. Simmons, et al. 1992a. “Colonization studies of various HVAC insulation materials,” pp. 101–5 in *Proceedings of IAQ ’92*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

Ahearn D. G., R. B. Simmons, J. Chafin, et al. 1992b. “Microorganisms associated with an odor-producing HVAC system,” in *Abstracts of the Annual Meeting of the Society for Industrial Microbiology*, Toronto, Canada.

Ahearn, D. G., R. B. Simmons, K. F. Switzer, et al. 1991. “Colonization by *Cladosporium* sp. of painted metal surfaces associated with heating and air conditioning systems,” *J Ind Microbiol* **8:** 277–80.

Andrae, S., O. Axelson, B. Bjorksten, M. Fredriksson, and N. M. Kjellman 1988. “Symptoms of bronchial hperreactivity and asthma in relation to environmental factors,” *Arch Dis Child* **63:** 473–78.

Arens, E. A., and A. V. Baughman 1996. “Indoor humidity and human health, Part 2: Buildings and their systems,” *ASHRAE Trans* **102:** 1–9.

Armstrong Laboratory 1992. *Occupational and Environmental Health Directorate*, Armstrong Laboratory, Brooks Air Force Base, Texas.

Arundel, A. V., E. M. Sterling, J. H. Biggin, and T. D. Sterling 1986. “Indirect health effects of relative humidity in indoor environments,” *Environ Health Perspect* **65:** 351–61.

Bakke, J. V., and F. Levy 1990. “Indoor air quality and climate in kindergartens— Relation to health effects,” 1:3–7 in *Proceedings of Indoor Air ’90*, International Conference on Indoor Air Quality and Climate, Toronto, Canada.

Bartlett, K. H., S. M. Kennedy, and M. Brauer 1998. “An evaluation of bioaerosol particulate in elementary school classrooms,” presented at the AIHA National Conference, Atlanta, May.

Batterman, S. A., and H. Burge 1996. “HVAC systems as emissions sources affecting indoor air quality: A critical review,” *HVAC&R Res* **1:** 61–80.

Bascom, R. 1997. “Plenary paper: Health and indoor air quality in schools—A spur to action or false alarm?” 1:3–13 in *Proceedings of Healthy Buildings/IAQ’97*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Bethesda, Md.

Baughman, A. V., and E. A. Arens 1996. “Indoor humidity and human health, Part 1: Literature review of health effects of humidity-influenced indoor pollutants,” *ASHRAE Trans* **102:** 10–19.

Bayer, C. W., and S. A. Crow 1992. “Odorous volatile emissions from fungal contamination,” pp. 99–104 in *Proceedings of IAQ ’92,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

Bayer, C. W., and S. A. Crow 1993. “Detection and characterization of microbially produced volatile organic compounds,” 6:297–302 in *Indoor Air ’93,* Proceedings of the 6th International Conference on Air Quality and Climate, July 4–8, Helsinki, Finland.

Bayer, C. W., S. Crow, and J. A. Noble 1995. “Production of volatile emissions by fungi,” pp. 101–9 in *Proceedings of IAQ ’95,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

Bayer, C. W., and C. C. Downing 1991. “Does a total energy recovery system provide a healthier environment?” pp. 74–76 in *Proceedings of IAQ ’92,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

Bayer, C. W., and C. C. Downing 1992. “Indoor humidity in schools with insufficient humidity control,” pp. 197–200 in *Proceedings of IAQ ’92,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

Bisett, J. 1987. “Fungi associated with urea-formaldehyde foam insulation in Canada,” *Mycopathologia* **99:** 47–56.

Bjurman, J. 1993. “Thermal insulation materials, microorganisms, and sick building syndrome,” 4:339–43 in *Indoor Air ’93,* Proceedings of the 6th International Conference on Air Quality and Climate, July 4–8, Helsinki, Finland.

Bjurman, J., and J. Kristensson 1992a. “Production of volatile metabolites by the soft rot fungus *Chaetomium globosum* on building materials and defined media,” *Microbios* **72:** 47–54.

Bjurman, J., and J. Kristensson 1992b. “Volatile production by *Aspergillus versicolor* as a possible cause of odor in houses affected by fungi,” *Mycopathologia* **118:** 173–78.

Boone, K., P. J. Ellringer, J. E. Sawyer, and A. Streifel 1997. “Can good indoor air quality improve the performance of elementary students?” 1:75–79 in *Proceedings of Healthy Buildings/IAQ’97,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Bethesda, Md.

Borjesson, T., U. Stollman, and J. Schnurer 1990. “Volatile metabolites and other indicators of *Penicillium aurantiogriseum* growth on different substrates,” *Appl Environ Microbiol* **56:** 3705–10.

Borjesson, T., U. Stollman, and J. Schnurer 1992. “Volatile metabolites produced by six fungal species compared with other indicators of fungal growth on cereal grains,” *Appl Environ Microbiol* **58:** 2599–2605.

Brady, John 1996. “Equipment earns high grades: HVAC in education,” *Engineered Systems Magazine*, August.

Clark, William 1996. “IAQ, CO_2 levels, and emotionally disturbed children: Is there a link?” *Air Conditioning, Heating, & Refrigeration News*, no. 33, June 24.

Coad, W. J. 1995. “Keynote address: Indoor air quality—a design parameter,” pp. 23–26 in *Proceedings of IAQ ’95,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

Croft, W. A., B. B. Jarvis, and C. S. Yatawara 1986. “Airborne outbreak of trichothecene toxicosis,” *Atmos Environ* **20:** 549–52.

Crow, S. A., and D. G. Ahearn 1997. “Fungal colonization of solid surfaces and the sick building syndrome,” pp. 216–20 in T. H. Connor and C. F. Fox., eds., *Biotechnology International,* Universal Medical Press, San Francisco.

Crow, S. A., D. G. Ahearn, and J. A. Noble 1995. “Survey of fungi in buildings in southeastern USA,” pp. 406–16 in *Proceedings of Engineering Solutions to Indoor Air Quality Problem*, July 22–24.

Crow, S. A., D. G. Ahearn, J. A. Noble, M. Moyenuddin, and D. L. Price 1993. “Ecology of fungi in buildings: Relationship to indoor air quality,” pp. 671–75 in *Proceedings of International Symposium: Measurement of Toxic and Related Air Pollutants,* Durham, N.C.

Crow, S. A., D. G. Ahearn, J. A. Noble, M. Moyenuddin, and D. L. Price 1994. “Microbial ecology of buildings: Fungi in indoor air quality,” *Amer Environ Laboratory* **2/94:** 16–18.

Cummings, J. B., and J. C. R. Withers. 1998. “Building cavities used as ducts: Air leakage characteristics and impacts in light commercial buildings,” *ASHRAE Trans* **104:** 1–10.

Daisey, J. M., and W. J. Angell 1998. *A Survey and Critical Review of the Literature on Indoor Air Quality, Ventilation and Health Symptoms in Schools,* LBNL-41517, Lawrence Berkeley National Laboratory, March.

Downing, C. C., and C. W. Bayer 1993. “Classroom indoor air quality versus ventilation rate,” *ASHRAE Trans* **99:** 1099–1103.

Dozier, J. 1992. “IAQ and the classroom,” *Heating/Piping/Air Conditioning,* August, pp. 59–62.

ELI (Environmental Law Institute) 1996. *Law and Policy Databases: Radon, Indoor Air Quality, and Electric and Magnetic Fields*, Washington, D.C., ELI, March.

Emanuel, J. A., F. J. Wenzel, and B. R. Lawton 1975. “Pulmonary mycotoxicosis,” *Chest* **67:** 293–97.

EPA (U.S. Environmental Protection Agency) 1998. *Sources of Information on Indoor Air Quality: Indoor Air Quality in Schools: Why IAQ Is Important to Your School,* EPA, Washington, D.C. Available online at http://www.epa.gov/iaq/schools/index/html.

Ezeonu, I. M., J. A. Noble, R. B. Simmons, et al. 1994. “Effect of relative humidity on fungal colonization of fiberglass insulations,” *Appl Environ Microbiol* **60:** 2149–51.

Ezeonu, I. M., D. L. Price, R. B. Simmons, et al. 1995. “Fungal production of volatiles during growth on fiberglass,” *Appl Environ Microbiol* **60:** 4172–73.

Fischer, J. C. 1996. “Optimizing IAQ, humidity control, and energy efficiency in school environments through the application of desiccant-based total energy recovery systems,” pp. 188–203 in *Proceedings of IAQ ’96,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Washington, D.C.

Flannigan, B. 1992. “Indoor microbiological pollutants—Sources, species, characterization and evaluation,” pp. 73–98 in H. Knoppel and P. Wolkoff, eds., *Chemical Microbiological, Health, and Comfort Aspects of Indoor Air Quality,* ECSC, EEC, EAEC, Brussels.

Flannigan, B., and P. R. Morey 1996. *Control of Moisture Problems Affecting Biological Indoor Air Quality*, TFI-1996, International Society of Indoor Air Quality and Climate, Ottawa, Canada, p. 3.

GAO (General Accounting Office) 1995. *School Facilities: Condition of America's Schools*, GAO/HEHS-95-61, U.S. GAO, Washington, D.C. Available online as text or PDF file (through search for report number) at http://www.access.gpo.gov/su_docs/aces/aces160.shtml.

GAO (General Accounting Office) 1996. *School Facilities: America's Schools Report Differing Conditions,* GAO/HEHS-96-103, GAO, Washington, D.C. Available online as text or PDF file (through search for report number) at http://www.access.gpo.gov/su_docs/aces/aces160.shtml.

Gatley, D. P. 1993. "Energy-efficient dehumidification technology," pp. 117–43 in *Bugs, Mold, and Rot II*, National Institute of Building Sciences, Washington, D.C.

Green, G. H. 1974. "The effect of indoor relative humidity on absenteeism and colds in schools," *ASHRAE Trans* **80:** 131–41.

Green, G. H. 1985. "Indoor relative humidities in winter and related absenteeism," *ASHRAE Trans* **91:** 643–53.

HPAC (Heating/Piping/Air Conditioning) 1990. "Environmental comfort's role in education," *Heating/Piping/Air Conditioning*, September, pp. 202, 204.

HPAC (Heating/Piping/Air Conditioning) 1996a. "School improves its air quality," *Heating/Piping/Air Conditioning*, March, pp. 24–25.

HPAC (Heating/Piping/Air Conditioning) 1996b. "Filtration brings IAQ/humidity control savings to school," *Heating/Piping/Air Conditioning*, August, pp. 23–25.

HPAC 1997. "Combining geothermal and dehumidification technologies helps school improve IAQ," *Heating/Piping/Air Conditioning*, July, pp. 15, 17.

Heinemann, S., H. Beguin, and N. Nolard 1994. "Biocontamination in air-conditioning," pp. 179–86 in R. A. Samson, M. E. Flannigan, B. Flannigan et al., eds., *Health Implications of Fungi in Indoor Environments*, Elsevier, Amsterdam, Netherlands.

Henderson, H. I., and K. Rengarajan 1996. "A model to predict the latent capacity of air conditioners and heat pumps at part-load conditions with constant fan operation," *ASHRAE Trans* **102:** 266–72.

Hirsch, D. J., S. R. Hirsch, and J. H. Kalbfleisch 1978. "Effects of central air-conditioning and meteorological factors on indoor spore counts," *J Allergy Clin Immunol* **62:** 22–26.

Hope-Simpson, R. E. 1958. "The epidemiology of non-infectious diseases," *R Soc Health J* **78:** 593.

Horner, W. E., P. R. Morey, and A. G. Worthan 1997. "Microbial VOC sampling in a moldy building investigation," pp. 593–601 in *Proceedings of Engineering Solutions to Indoor Air Quality Problems*, Air and Waste Management Association, Research Triangle Park, N.C.

Jarvis, B. B. 1990. "Mycotoxins and indoor air quality," pp. 234–56 in P. R. Morey, J. C. Feeley, Sr., and J. A. Otten, eds., *Biological Contaminants in Indoor Environments*, American Society for Testing and Materials, Philadelphia.

Johanning, E., P. R. Morey, and M. Goldberg 1993. "Remedial techniques and medical surveillance program for handling of toxigenic *Stachybotrys atra*," 4:311–16 in

Proceedings of Indoor Air ’93, Proceedings of the 6th International Conference on Air Quality and Climate, July 4–8, Helsinki, Finland.

Joki, A., V. Saano, T. Reponen, and A. Nevalainen 1993. “Effect of indoor microbial metabolites on ciliary function in respiratory airways,” 1:259–63 in *Proceedings of Indoor Air ’93,* Proceedings of the 6th International Conference on Air Quality and Climate, July 4–8, Helsinki, Finland.

Lebowitz, M. D., and D. S. Walkinshaw 1992. “Indoor Air ’90: Health effects associated with indoor air contaminants,” *Arch Environ Health* **47:** 6–7.

Lstiburek, J. 1994. *Mould, Moisture, and Indoor Air Quality. A Guide for Designers, Builders, and Building Owners,* Building Science Corporation, Chestnut Hill, Mass.

Lytton, M. 1997. “Making the connection between educational facilities and productivity,” in *Proceedings of Healthy Buildings ’97,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Washington, D.C.

McLoughlin, J., M. Nall, B. Isaacs, J. Petrosko, J. Karibo, and B. Lindsey 1983. “The relationship of allergies and allergy treatment to school performance and student behavior,” *Ann Allergy* **51:** 506–10.

Maroni, M., M. Bersani, D. Cavallo, et al. 1993. “Microbial contamination in buildings: Comparison between seasons and ventilation systems,” 4:137–42 in *Proceedings of Indoor Air ’93,* Proceedings of the 6th International Conference on Air Quality and Climate, July 4–8, Helsinki, Finland.

Meckler, G. 1992. “HVAC system characteristics: Ventilation and energy,” pp. 327–33 in *Proceedings of IAQ ’92,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

Merrill, J. L., and A. TenWolde 1989. “Overview of moisture-related damage in one group of Wisconsin manufactured homes,” *ASHRAE Trans* **95:** 405–14.

Miller, J. D. 1992. “Fungi and the building engineer,” pp. 147–59 in *Proceedings of IAQ ’92,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

Mishra, S. K., L. Ajello, D. G. Ahearn, et al. 1992. “Environmental mycology and its importance to public health,” *J Med Vet Mycol* **30** (suppl. 1): 287–305.

Morey, P. R. 1988. “Experience on the contribution of structure to environmental pollution,” pp. 40–79 in R. B. Knudisin, ed., *Architectural Design and Indoor Microbial Pollution,* Oxford University Press, New York.

Morey, P. R. 1992. “Microbiological contamination in buildings: Precautions during remediation activities,” pp. 94–100 in *Proceedings of IAQ ’92,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

Morey, P. R. 1993. “Microbiological events after a fire in high-rise building,” 4:323–27 in *Proceedings of Indoor Air ’93,* Proceedings of the 6th International Conference on Air Quality and Climate, July 4–8, Helsinki, Finland.

Morey, P. R., and C. M. Williams 1991. “Is porous insulation inside an HVAC system compatible with a healthy building?” pp. 128–35 in *Proceedings of IAQ ’90,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

Moss, M. O. 1991. “The environmental factors controlling mycotoxin formation,” pp. 125–40 in J. E. Smith and R. S. Henderson, eds., *Mycotoxins and Animal Foods,* CRC Press, Boca Raton, Fla.

Mouilleseaux, A., F. Squinazi, and B. Festy 1993. “Microbial characterization of air quality in classrooms,” 4:195–200 in *Proceedings of Indoor Air ’93*, Proceedings of the 6th International Conference on Air Quality and Climate, July 4–8, Helsinki, Finland.

Nelson, H. S., S. R. Hirsch, J. L. Ohman, et al. 1998. “Recommendations for the use of residential air cleaning devices in the treatment of allergic respiratory diseases,” *J Allergy Clin Immunol* **2:** 661–69.

Nevalainen, A. 1993. “Microbial contamination of buildings,” in vol. 4 of *Proceedings of Indoor Air ’93*, Proceedings of the 6th International Conference on Air Quality and Climate, July 4–8, Helsinki, Finland.

Nikulin, M., S. Berg, E. Hintikka, and Pasanen, A. 1993. “Production of stachybotryotoxins on some building materials at different relative humidities and temperatures,” 4:397–400 in *Proceedings of Indoor Air ’93*, Proceedings of the 6th International Conference on Air Quality and Climate, July 4–8, Helsinki, Finland.

NIOSH (National Institute for Occupational Safety and Health) 1989. *Indoor Air Quality: Selected References,* NIOSH, Cincinnati.

Price, D. L., I. M. Ezeonu, R. B. Simmons, P. R. Morey, and D. G. Ahearn 1995. “Fungal colonization and water activity studies of heating ventilating and air conditioning system insulation materials from a sick building,” pp. 321–24 in *Proceedings of Indoor Air—An Integrated Approach*, Elsevier, Netherlands.

Price, D. L., R. B. Simmons, I. M. Ezeonu, et al. 1994. “Colonization of fiberglass insulations used in HVAC systems,” *J Ind Microbiol* **13:** 154–58.

Richards, W. 1986. “Allergy, asthma, and school problems,” *J School Health* **56:** 151–52.

Ritzel, G. 1996. “Ozialmediz insche erhebungen zur pathoggenese und prophyaare von erkaltungskankheiten,” *Z. Praventirmed* **11:** 9–16.

Romm, J. J. 1994. *Lean and Clean Management: How to Boost Profits and Productivity by Reducing Pollution*, Kodansha International, New York.

Romm, J. J., and W. D. Browning 1994. *Greening the Building and the Bottom Line: Increasing Productivity through Energy-Efficient Design*, Rocky Mountain Institute, Snowmass, Colo.

Sale, G. S. 1972. “Humidification to reduce respiratory illness in nursery school children,” *South Med J* **65:** 7.

Samet, J. M., M. C. Marbury, and J. D. Spengler 1988. “Health effects and sources of indoor air pollution. Part II,” *Am Rev Resp Dis* **137:** 221–42.

Samson, R. A., B. Flannigan, M. F. Flannigan, A. P. Verhoeff, O. C. G. Adan, and E. S. Hoekstra 1994. *Health Implications of Fungi in Indoor Environments,* Elsevier/North-Holland Biomedical Press, Amsterdam, Netherlands.

Smedje, G., D. Norback, and C. Edling 1997. “Subjective indoor air quality in schools in relation to exposure,” *Indoor Air* **7:** 143–50.

Smedje, G., D. Norback, B. Wessen, and C. Edling 1996. “Asthma among school employees in relation to the school environment,” 1:611–16 in *Proceedings of Indoor Air ’96*, Nagoya, Japan.

Smith, J. E., and A. Hacking 1983. “Fungal toxicity,” 4:238–65 in J. E. Smith, D. R. Berry, and B. Kristiansen, eds., *The Filamentous Fungi*, Edward Arnold, London.

Sorenson, W. G. 1991. “Mycotoxins as potential occupational hazards,” *J Ind Microbiol*, Supplement, 5:205–11.

Sorenson, W. G., D. G. Frazer, B. B. Jarvis, et al. 1987. “Trichothecene mycotoxins in aerosolized conidia of *Stachybotrys atra*,” *Appl Environ Microbiol* **53:** 1370–75.

Strom, G., J. West, B. Wessen, and U. Palmgren 1994. “Quantitative analysis of microbial volatiles in damp Swedish houses,” pp. 291–305 in R. A. Samson, B. Flannigan, and M. E. Flannigan et al., eds., *Health Implications of Fungi in Indoor Air Environments*, Elsevier/North-Holland Biomedical Press, Amsterdam, Netherlands.

Sundell, J., and T. Lindvall 1993. “Indoor air humidity and the sensation of dryness as risk indicators of SBS,” *Indoor Air* **3:** 82–93.

Tucker, G. 1986. “Research overview: Sources of indoor air pollutants,” pp. 395–404 in *Proceedings of IAQ ’96,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Washington, D.C.

Turner, W. A., S. M. Martel, L. M. Belida, L. Rogers, and E. Gordon 1996. “The Advantage Classroom™: Designing to achieve better indoor air quality and thermal comfort to improve the learning environment,” pp. 1–11 in *Proceedings of IAQ ’96*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Baltimore, Md.

Tyrrell, D. A. 1965. *Common Colds and Related Diseases,* Edward Arnold Publisher, London.

Walinder, R., D. Norback, G. Wieslander, G. Smedje, and C. Erwall 1997. “Nasal mucosal swelling in relation to low air exchange rate in schools,” *Indoor Air* **7:** 198–205.

West, M. K., and E. C. Henson 1989. “Determination of material hydroscopic properties that affect indoor air quality,” pp. 224–31 in *Proceedings of IAQ ’89*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

Womble, S. E., R. Axelrad, J. R. Girman, R. Thompson, and R. Highsmith 1993. “EPA BASE program—Collecting baseline information on indoor air quality,” 1:821–25 in *Proceedings of Indoor Air ’93,* Proceedings of the 6th International Conference on Air Quality and Climate, July 4–8, Helsinki, Finland.

Zeringue, H. J., D. Bhatnagar, and T. E. Cleveland 1993. “$C_{15}H_{24}$ volatile compounds unique to aflatoxigenic strains of *Aspergillus flavus*,” *Appl Environ Microbiol* **59:** 2264–70. ❖

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