HVAC Systems As Emission Sources Affecting Indoor Air Quality: A Critical Review

Stuart A. Batterman, Ph.D.
Associate Member ASHRAE

Harriet Burge, Ph.D.

This study evaluates literature on heating, ventilating and air conditioning (HVAC) systems as contaminant emission sources that affect indoor air quality (IAQ). The various literature sources and methods for characterizing HVAC emission sources are reviewed. Characterization methods include in situ *tests, longitudinal and cross-sectional studies, and laboratory studies. A critique of the literature reveals that few studies are well-controlled, comprehensive and quantitative. Significant gaps in the data are highlighted and procedures are suggested to improve the characterization of bioaerosol and VOC (volatile organic compound) emission sources. Several HVAC components are cited frequently as emission sources, and there is broad agreement regarding their significance. These sources include biological growth and bioaerosol generation in the presence of moisture provided by air washers and other recirculating water systems, or by poor control of humidity, badly designed humidifying systems, and inadequately maintained cooling coils and drip pans. IAQ problems appear exacerbated by dust accumulation, and by the presence of fibrous insulation. Other problems include entrainment, migration, and infiltration of indoor and outdoor contaminants that are distributed to indoor spaces by the HVAC system. The importance of good design and operation of HVAC systems, including the appropriate placement and maintenance of air intakes, building pressurization, and local exhaust in source areas, is also well accepted. More limited data implicate dust (resulting from inadequate filtration and maintenance of filters) as a secondary source for VOCs.*

INTRODUCTION

The view that closing buildings and recirculating air can significantly affect indoor air quality (IAQ) is not new. Woods (1983) cited Leeds quoting Benjamin Franklin's correspondence to a physician:

> "I considered [fresh air] an enemy, and closed with extreme care every crevice in rooms I inhabited. Experience has convinced me of my error. I am persuaded that no common air from without is so unwholesome as the air within a closed room that has been often breathed and not changed. You physicians have of late discovered, after a contrary opinion had prevailed some ages, that a fresh and cool air does good to persons in the small-pox and other fevers. It is to be hoped, that in another century or two we may find out that it is not bad even for people in health."

We are operating, however, on the premise that heating, ventilating and air conditioning (HVAC) systems are essential to modern life, and that, when properly designed, installed, operated and maintained, HVAC systems do provide healthy, comfortable indoor environments. However, it has recently been suggested that problem building syndrome and occupant complaints are related primarily to mechanical ventilation.

Stuart A. Batterman is a professor of Environmental and Industrial Health at the University of Michigan, Ann Arbor, Michigan. **Harriet Burge** is a professor of Environmental Health at the Harvard School of Public Health, Harvard University, Massachusetts.

(Buildings which exhibit some indoor air quality problems are sometimes commonly referred to as "sick buildings.") In a questionnaire-based investigation of 43 British office buildings, Burge et al. (1987) found that complaints occurred more frequently in buildings where HVAC systems provided cooling and humidification. In the US, NIOSH blamed inadequate ventilation for complaints in 52% of 484 buildings (Crandall 1987). Health and Welfare Canada found the same percentage in 1362 Canadian buildings (Kirkbride et al. 1990). In apportioning emission sources affecting IAQ, Fanger et al. (1988), Pejtersen et al. (1991) and Molhave and Thorsen (1991) attributed a large fraction of perceived air degradation to pollutant sources within HVAC systems.

As emission sources, HVAC systems are poorly characterized in comparison to other sources of air pollutants in buildings, such as building materials, furnishings, cleaning products, and personal-use products. This has occurred for several reasons. HVAC systems are usually considered to improve IAQ by diluting, filtering and removing contaminants, and until recently have not been considered as sources. However, HVAC systems can have complex and time-varying effects on contaminant emissions and transport, sometimes acting as sinks, and other times as sources, resulting in several practical difficulties when characterizing emissions. Finally, HVAC components and systems are large and complex, and rarely amenable to chamber studies, composition analyses or other tests that provide the desired degree of experimental control and relevance to operating conditions.

Over the last decade, IAQ concerns have prompted many studies of pollutant emission sources, transport processes, health effects, mitigation strategies, and other aspects. This review focuses on the HVAC system as a source of pollutants, either intrinsically from off-gassing or the release of particles from components, or because of contamination.

This review draws on published literature that can be divided into four categories: data in peer-reviewed journals; data in books and proceedings; reviews in peer-reviewed journals; and reviews in books or proceedings. Relatively little peer-reviewed literature exists in the area of HVAC emission sources. Much of what is available deals primarily with health effects, and indicates that, under some conditions, HVAC systems do adversely affect human health and comfort. The proceedings literature contains most of the published data regarding HVAC systems as pollutant sources. Care must be taken in interpreting proceedings literature, which ranges from reports of nearly complete studies to speculations based on small data sets derived from limited studies. Literature reviews can provide, as we hope this one does, an overview of the subject that benefits from the reviewer's interpretations based on experience. Nonetheless, it is important to return to the peer-reviewed literature to support critical decisions. Good general reviews of IAQ problems specifically related to HVAC systems have been published by Woods (1983), Hughes and O'Brien (1986), Morey and Shattuck (1989), and Moseley (1990). Reviews emphasizing microorganisms in HVAC systems are provided by McClunney (1987), Breif and Bernath (1988), and Burrell (1991). Particle filtration issues are discussed by Ottney (1993), and duct cleaning is surveyed by Luoma et al. (1993). This review focuses on the peer-reviewed journal literature, and on papers in the proceedings literature known to be of similar quality to peer-reviewed literature.

APPROACHES TO IDENTIFYING AND CHARACTERIZING HVAC SOURCES

HVAC emission sources can be investigated using several approaches:

1. Case reports
2. *In situ* component studies
3. Longitudinal studies of HVAC and building systems
4. Cross-sectional studies of HVAC and building systems
5. Chamber or other laboratory tests of HVAC system components

Case Reports

Nearly all of the literature relevant to HVAC emission sources consists of anecdotal case reports of investigations of individual buildings or small groups of buildings. Typically, case reports describe the motivation and/or purpose of the IAQ investigation, essential features of the building and HVAC system, and summaries of results of visual inspection, contaminant monitoring, and HVAC or source analyses. Reports sometimes include occupants' symptoms, suggested mitigation strategies, and results of mitigation efforts. Case reports generally focus on problem buildings and thus help to identify many potential HVAC emission sources. However, case reports do not reveal a systematic and representative picture of emission sources in HVAC systems. Quantification of results is rarely emphasized or even possible, based on the data presented. Good case reports published in the journal literature include Banaszak et al. (1970), Bernstein (1983), Fink et al. 1976, Flaherty et al. 1984, Hodgson et al. (1987), McJilton et al. (1990), all of which deal with microbiological contamination, and Burton (1990) in the unreviewed literature, which is a study of re-entrainment.

In Situ Component Studies

In situ component studies can be used to identify and characterize emission sources from HVAC system components. By monitoring the concentration increment ΔC_i (mg/m^3) across a component for contaminant i, i.e., the difference between upstream and downstream concentrations, the emission rate E_i (mg/h) for the component can be estimated as:

$$E_i = \Delta C_i Q \tag{1}$$

where Q is the flow rate (m^3/ h). For surfaces, area emission rates [mg/(h$\cdot$m^2)] may be derived by dividing by the source's surface area. This approach is potentially applicable for vapors and aerosols released from duct surfaces, filters, heating/cooling coils, fans, silencers, etc.

The estimation of *in situ* emission rates requires many assumptions with respect to conditions in the system, source characteristics, and sampling.

Good mixing is assumed, as normally expected in HVAC systems (Molhave and Thorsen 1991). In cases of poor mixing, as possibly in mixing boxes, a velocity-weighted concentration increment may be needed, as obtained using a number of transects with simultaneous measurements of air velocity and concentration. Since emissions might be affected by temperature, pressure, flow rates, and other factors, these parameters should remain constant over the measurement period. HVAC systems that cycle on and off may require monitoring over a number of cycles to reflect intermittent conditions. Alternatively, if the effect of these parameters on the emission rate is known, one might carefully measure these parameters and calculate the role of each in the measured emission rate. Air leakage into the system near the component being tested, either present initially or as a result of the monitoring, must be avoided. Leakage is likely when the component is under negative pressure.

Emission rates are assumed to be constant over the measurement period. For particles, desorbing VOCs and any other pollutant with a finite reservoir, this criterion is unlikely to be met. For example, fungus spores resulting from active growth on surfaces are produced in batches, over periods of time and in concentrations that depend on ambient conditions. Amplification of biological agents in HVAC reservoirs may occur while the system is inoperative (i.e., during shut-down periods), with bursts of emission occurring when the system is turned on. This means that multiple measurements must be taken over short periods to characterize these emissions. For vapors, local equilibrium must be assumed, thus, desorbing (source) or absorbing (sink) processes are assumed to be balanced. Alternatively, non-equilibrium assumptions may be invoked to quantify emissions during desorbing periods.

Upstream and downstream measurements should be made simultaneously. Monitoring must avoid any disturbances to the HVAC system to prevent measurement artifacts.

Because ΔC_i is normally small, especially in comparison to ambient or in-duct levels, concentration measurements must be precise to detect small increments, and representative to avoid anomalies. *In situ* gaseous measurements are straightforward. Accurate particulate measurements, however, require isokinetic sampling for particles with diameters exceeding about 5 µm, which may be difficult or impossible without accessible and favorable duct configurations. The accuracy of aerosol sampling may also be compromised in variable air volume systems where air velocities are changing. Particulate sampling also must consider: the large range of particle diameters of interest (e.g., 0.01 to perhaps 100 µm dia.); the need to maintain viability of biological agents for culturing and identification; and the large sample sizes needed to quantify mass. These constraints greatly restrict the utility of most types of particulate measurements, and essentially prohibit the use of commercially available culture-plate bioaerosol samplers.

An alternative to emission-rate determination is to evaluate HVAC components *in situ* for the potential release of pollutants. This, in fact, is the procedure generally used to document the presence of specific pollutants in most case studies (Hugenholtz and Fuerst 1992). Usually, the system is carefully inspected, and sampling sites are chosen on the basis of visible contamination, or because known pollutant reservoirs are present. Bulk samples of material from each site are analyzed to verify the nature and strength of the potential source, and air samples are collected under as representative conditions as is possible. For biological agents, the system is usually shut down, and air samples collected immediately in the vicinity of the suspected source, and in other areas of the system. Sometimes, deliberate disturbances of the site may be used to create a "worst case" situation. Ambient (room) air and outdoor air are collected to determine the contribution of specific pollutants from the suspected site of contamination.

Another type of *in situ* test uses side-by-side comparisons of alternate materials or, possibly, systems in the same building, air handler, duct, etc. This approach has been used to test resistance to microbial infestation in colonization studies (e.g., Ahearn et al. 1992), and appears adaptable to other studies, e.g., dust accumulation on variously coated surfaces.

Longitudinal Studies

The role of HVAC systems in IAQ can be characterized using longitudinal studies in which HVAC system components, ventilation rates, occupancy, and other factors are usually altered in one building during interventions that typically last periods from hours to weeks. IAQ impacts of the interventions are determined by comparison to the earlier (baseline) condition. Variations of this approach have been used to estimate HVAC systems as emission sources and to evaluate effects on IAQ of different ventilation and air exchange rates.

Several studies have used an approach suggested by Fanger et al. (1988) to estimate emissions from three broad source classes:

1. HVAC system
2. Occupant and occupant-related activities
3. Building materials, furnishings, and other interior constituents

These estimates are obtained using three sets of IAQ measurements and a simple IAQ model:

$$C_{indoor,\,t} = C_{outdoor,\,t} + E_{total}/Q_{exchange,\,t} \qquad (2)$$

$$E_{total} = E_{HVAC} + E_{occupant} + E_{building} \quad (3)$$

where C_{indoor} and $C_{outdoor}$ are indoor and outdoor IAQ measurements, e.g., concentrations of specific pollutants (mg/m^3), and $Q_{exchange}$ is the exchange rate (m^3/h), usually measured with a tracer gas. Subscript t denotes the time dependence of par-ameters. E_{total} is the source strength of all sources, including those related to the HVAC system (E_{HVAC}), occupancy and occupant activities ($E_{occupant}$), and building materials, furnishings, etc. ($E_{building}$). The emission term in Equation (2) is solved by monitoring or estimating levels of specific pollutants indoors and out, and by measuring exchange rates. To separate the emissions terms in Equation (3), measurements of C_{indoor} and $Q_{exchange}$ are taken under three conditions:

1. Occupancy with HVAC system functioning, giving

$$E_{HVAC} = E_{occupant} + E_{building}$$

2. Occupancy with HVAC system off or blocked from the space under study, giving

$$E_{occupant} + E_{building}$$

3. No occupancy, with the HVAC system operating, giving

$$E_{HVAC} + E_{building}$$

The IAQ measurements can include physical-chemical or biological characterizations as well as results from sensory panels. Results are assumed to represent steady-state conditions, and only the aggregate HVAC impact, rather than those from specific components, is identified. An alternate longitudinal approach has been used by Menzies et al. (1993) in which ventilation and exchange rates were varied. Both physical-chemical measurements and sensory and symptom data were collected. Unfortunately, this study did not achieve a large or representative range of ventilation and exchange rates. As in the approach by Fanger et al. (1988), only the aggregate HVAC impact can be determined from this kind of study.

A combination of longitudinal and *in situ* studies can be used to isolate specific sources. The activities of specific emission sources are determined and then a multiple regression analysis is used to estimate time-varying emissions from the sources (Franke and Wadden 1987). For HVAC sources, this regression resembles:

$$C_t = \frac{\beta_o + \sum_{i=1}^{p} \beta_i X_{i,t}}{Q_{exchange,t}} \quad (4)$$

where C_t is the measured concentration of a specific pollutant at time t; B_i (mg/activity) are least-squares estimates of the emission factor for source i; $X_{i,t}$ is the activity or intensity of source i of p sources; and $Q_{exchange,t}$ (m^3/h) is the exchange or airflow rate. This approach requires that source activities be measurable and varying in time, and that all confounding variables, e.g., sources that emit the same pollutant, be controlled or measured. This approach appears applicable to several HVAC components. For example, emissions of anticorrosive agents from steam humidifiers might be estimated using humidifier steam consumption as dependent variable $X_{i,t}$. Results for HVAC components using this approach have not been published.

Case-control comparisons are a variant of longitudinal studies that include some aspects of cross-sectional studies (described below). They may offer one of the more sensitive and reliable methods of investigating effects because controls are incorporated that adjust for variations in occupancy, weather, environmental factors (such as ambient levels of the pollutants of interest), and other potentially confounding variables that may be encountered over the study period. This approach permits the determination of odds-ratios and other indicators showing the impact of the intervention with respect to the control case. Case-control studies appear especially useful for tests that require long study periods.

Longitudinal studies have several limitations. Firstly, the ability to alter HVAC system operation is often limited. While HVAC system schedules can be altered, filters can be replaced, and ventilation and exchange rates modified within narrow ranges, many components cannot be tested. Secondly, longitudinal studies are time consuming. Interventions may require several weeks or possibly years for a full evaluation. Thirdly, in case-control studies, two comparable buildings or spaces that can be individually controlled and monitored must be studied simultaneously. This approximately doubles the level of effort and expense.

Cross-Sectional Studies

Cross-sectional studies of HVAC systems involve collecting data on a single occasion in many buildings. HVAC system emissions can be identified using cross-sectional studies in buildings with different system types and components. For example, Burge et al. (1987) studied complaint rates as a measure of IAQ in groups of buildings with natural ventilation, mechanical ventilation without cooling, and mechanical ventilation with cooling. Such comparisons require that confounding factors be controlled or corrected. Thus, it may be necessary to use building types, occupant densities, smoking policies, exchange rates, interior equipment, geographic regions, etc., that are similar in all study buildings. Statistical adjustment for dissimilarities may be possible; in some cases, however, this is difficult, given the strength and diversity of confounding factors, and a large sample size is needed to obtain statistically meaningful results. The likelihood of unknown, uncertain, unmeasured, or difficult to quantify factors decreases the statistical power to distinguish and evaluate HVAC emission sources in cross-sectional studies. Furthermore, surveys may not provide sufficient detail to evaluate specific HVAC sources and source interactions. Cross-sectional analyses of HVAC emission sources have not been published.

Laboratory Tests

Laboratory tests include collecting material from buildings and performing laboratory analyses, and testing of new materials for performance or release of pollutants. Laboratory component studies have been used for many years to determine filter efficiencies in tests that compare upstream and downstream contaminant levels. Similar tests have also been used to determine filter shedding, and to evaluate HVAC components for biological contamination or the potential for such contamination. Laboratory tests are essential to characterize complex sources, e.g., biological growth (Pasanen et al. 1991b).

Environmental test chambers are routinely used to measure VOC emissions under controlled temperatures, humidities, airflows, and loading ratios designed to reflect interior conditions and environments. U.S. EPA has developed standardized protocols for small chamber tests (Tichenor 1989; ASTM 1991) that provide good precision and accuracy. Certain HVAC components appear amenable to such tests, including materials that potentially outgas (e.g., caulks, sealants, paints, etc.). Similar tests have been performed for odors and VOCs from filters (Hujanen et al. 1991; Rivers et al. 1992), although EPA protocols were not used in these cases. Also, modifications of the chamber setup permit the evaluation of sorption-desorption processes (Rothenburg et al. 1989).

Although chambers provide a controlled environment so that individual characteristics of HVAC components can be tested, laboratory conditions can never truly duplicate dynamic building conditions; thus the quantification of emission rates may not be relevant for some HVAC components. This is unlikely to be an issue for VOCs that are rapidly outgassed, e.g., "wet" products like caulks and sealants. Chamber measurements may not accurately represent VOC emissions that depend on the previous time history of concentrations, humidities, etc. Chambers may not realistically simulate high flows, turbulence, fan cycling, etc., and thus may not account for entrainment and aerosolization, critical processes for some particulate emissions.

Summary

A wide range of methods is available to identify and estimate emissions from HVAC sources. While all methods have limitations, many are complementary. The most reliable results will be obtained using a combination of methods. For example, case reports may identify a suspected problem; laboratory component or chamber studies may identify and confirm specific emissions, or may allow identification of specific pollutant reservoirs; *in situ* tests may help quantify emissions or document the potential for emissions; and longitudinal and/or cross-sectional studies may confirm and extend results. At this point, no HVAC component has progressed through all of these stages for any pollutant.

HVAC SYSTEMS AND IAQ

The literature verifies that HVAC systems can be sources for some pollutants, although the extent and human health impact of the problem remains unknown. Table 1 provides an overview of HVAC emission sources and problems that are discussed below. Understanding the kinds of pollutants that can be generated in HVAC systems should help to direct efforts at control so that impacts can be minimized.

Table 1. Emission sources and problems identified in HVAC systems

SOURCES AND PROBLEMS	TYPICAL EXAMPLES
Intrinsic emission sources	
1. *Seals, caulks, adhesives*	outgassing of VOCs, deterioration
2. *Fibers*	asbestos, fiber shedding
3. *Metal degradation products*	deterioration and entrainment of coatings, platings, metal surfaces
4. *Lubricating oils, etc.*	fans, motors in the air stream
5. *Ozone*	release by electrostatic air cleaners
Emission sources resulting from contamination	
1. *Dust*	construction material, skin cells, etc., with accumulation possibly leading to microbial contamination, VOC sorption-desorption, and low flows
2. *Other organic debris*	leaves, bird droppings
3. *Growth of microorganisms*	growth and aerosolization of bioaerosols and VOCs from micro-organisms at sites including: cooling coils, drain pans, drains, traps and sumps, filters, insulation, duct surfaces, plenums, humidifiers and evaporative coolers, cooling towers
4. *VOC sinks*	filters, sound absorbers, insulation materials, deposited dust
5. *Cleaning compounds and biocides*	biocides, disinfectants, deodorizers
6. *Boiler steam*	anticorrosives, biocides, slimicides, oxygen-scavenging or filming chemicals, anti-corrosives, pH control neutralizers
Design/operational effects on IAQ	
1. *Entrainment and re-entrainment*	leaks, polluted outside air, building exhaust
2. *Rotary heat exchangers*	sorption-desorption of VOCs
3. *Building pressurization*	intake of polluted outside air
4. *Transport*	odor, VOC and particle migration
5. *Climate control*	high humidity
6. *Ventilation and air exchange*	inadequate dilution of internal sources, inadequate outside air

Intrinsic Emission Sources

Seals, Caulks, Etc. Based on laboratory component tests, adhesives, sealants and caulks used in HVAC systems can contain latex acrylic, styrene, butadiene rubber, neoprene rubber, butyl rubber, vinyl, silicone, and urethane (Leovic et al. 1993). These and other compounds may be released in the curing and aging of these products and, if they are placed in contact with HVAC air streams, then emissions may enter occupied spaces. No studies have been found that estimate IAQ impacts of these sources. However, standardized chamber tests can be used to provide accurate measurements of VOC composition and source strength for these materials, from which impacts may be estimated. Like other "wet" products, these materials are likely to exhibit emissions which rapidly decrease or decay after application (Tichenor and Mason 1988).

Fibers. Fibers from fiberglass linings damaged during installation or worn and disintegrating may be entrained and discharged to occupied spaces (Morey and Shattuck 1988). Spray-on fibrous fireproofing and exposed fibrous insulation in plenums may become dislodged and entrained (Morey and Shattuck 1989). Shumate and Wilhelm (1991) used laboratory tests to investigate fiber shedding for various types of filters. Only minimal amounts of fiber were shed in short and long term tests.

Price and Crump (1992) review releases of asbestos containing materials found in older HVAC systems. These particles may be released during building and HVAC maintenance and repair operations. Asbestos contamination and mitigation measures are well established and beyond the scope of this review.

Metal Degradation Products. Deterioration of platings on metal surfaces and subsequent entrainment may release particles containing toxic metals (e.g., Zn and Cd). One study did find that a small subset of dust particles contained high concentrations of Fe, Cr and Mn (Rothenberg et al. 1989); however, the source of these particles is unknown. Also poorly studied, microbial agents metabolize metals, and can produce metal-containing gases and aerosols.

Lubricating Oils, Etc. Levin and Moschandreas (1990) mention lubricating oils in fans and motors as potential VOC sources. Morey (1990a) recommends that motors should be located outside of ventilation air streams, possibly for the same reason. No study substantiating this source has been identified.

Ozone. Electrostatic air cleaners produce ozone (O_3) as a consequence of the electrostatic field used to ionize and collect particles. This phenomenon is well-known (Viner et al. 1992). Most units produce O_3 increments below 50 ppb (parts per 10^9 parts by volume), the EPA guideline, and well below the 120 ppb ceiling established as a National Ambient Air Quality Standard (NAAQS). The significance of this source increases, however, in areas where ambient or building air approaches or exceeds the O_3 standard.

Emission Sources Resulting from Contamination

Dust. Dust is an accumulation of particles entrained from outside air, and from air recirculated from the ventilation system and the occupied space. Dust accumulates on filters and on surfaces within the HVAC system. Outdoor dust contains (among other things) silica, combustion products, rubber, fungus spores, bacteria, and other whole and fragmented organisms. Laatikainen et al. (1991) found that dust loadings were related to the height of the air intake and the filter type used. Pasanen et al. (1992a) investigated surface density and accumulation rates of dusts and pollen. Dust accumulation depended on filter efficiency (including leakage between filters and frames).

Dust particles released from ventilation system components include fibers, rubber from fan belts, metal degradation products (see above), and particles from microbial sources. Dust from occupied spaces consists primarily of human skin scales, along with fibers, combustion products, and microorganisms. It should be noted that return ducts typically do not employ filtration, and low velocity returns and ceiling plenums can accumulate significant levels of dust and debris.

In an *in situ* study, Krzyanowsksi (1992) observed particulate "puffs" downstream of filters when HVAC system fans were turned on during fan cycling. Based on optical particle counter measurements, puffs consisted largely of small (0.5 to 1 μm dia.) particles, possibly previously settled material that was reentrained, or a burst of particles jarred from the filter bank.

Laatikainen et al. (1991) analyzed 17 samples of duct dust, measuring deposition rates, fungal spores, bacteria, pollen and total protein concentrations. Inorganic residues comprised the bulk (58 to 91%) of the dust, but concentrations of fungal spores and bacteria were high and highly correlated. Nyman and Sandstrom (1991) found high levels of culturable spores and bacteria in supply ducts. Levels decreased along the duct, suggesting removal by deposition.

No effect on air flow rates was seen as a function of dust loading by Pasanen et al. (1992a). However, all loading rates were low. In contrast, studies by Wallin (in Luoma et al. 1993) found a 20 to 30% increase in air flows after duct cleaning, although case study buildings had small and very dirty ducts. Luoma et al. (1993) suggest that the main reason for preventive duct cleaning is to minimize the possibility of microbial growth that would be likely in dirty ducts should water leaks or high humidity conditions occur, rather than to prevent particle resuspension or maintain air flows.

Dust can act as a direct source of VOC emissions, especially for odiferous particles like cigarette smoke and biological VOCs. Reemission of VOCs from extremely dirty ducts has been implicated as an indirect source of VOC emissions in a chemical laboratory environment (Downing and Bayer 1991). Molhave and Thorsen (1991) quantify VOC emissions from dust and debris from a 16 year old office building containing smokers, a small kitchen and cafeteria. Based on in-duct concentration differences, the HVAC duct was estimated to emit 161 mg/h of TVOCs, an emission rate four times higher than the HVAC filters (42 mg/h), or the internal sources in the cafeteria (44 mg/h). Thus, VOCs from dust are implicated as a major VOC source. This study, which has not been repeated, does not include replicates, has fairly high detection limits of 50 $\mu g/m^3$, and provided only preliminary speciation of the VOCs. (Heptane, hexane, and three other unidentified alkanes in both room air and ducts were identified.) VOC speciation was not used to apportion sources. Using a sensory panel, Hujanen et al. (1991) evaluated odors from dirty filters removed from AHUs in office buildings. Odor strength was associated with filter age, buildings in polluted areas, and possibly several unmeasured variables that included outdoor particulate concentrations and the chemical composition of the filter loadings. Given the building space under study, filter emissions probably resulted from cigarette smoke (Morey 1990a) and food odors.

VOC sorption and desorption on dust in HVAC filters and ducts may help explain results obtained by Fanger et al. (1988), Downing and Bayer (1991), Molhave and Thorsen (1991), Pejtersen et al. (1993) and others. Dust can contain hundreds of VOCs and semivolatile compounds. Laboratory studies examining the surface area, adsorption, and desorption of dust have been completed by Rothenberg et al. (1989), Kjaer and Nielsen (1993), and others. The VOC composition of dusts and fibers has been measured by Wilkins et al. (1993) and has been shown to demonstrate some explanatory power with respect to mucous membrane irritancy and concentration difficulty in a small cross-sectional study. However, these results have not yet been directly linked to HVAC system performance.

Pejtersen et al. (1992) and others (Anom. 1991) have noted that odors from ducts decreased substantially after duct cleaning.

Other Organic Debris. Absence of bird screens permits roosting inside air intakes, accumulation of bird droppings, and the risk of exposure to the infectious fungi *Histoplasma* and *Cryptococcus*, as well as other fungi and bacteria (Burrell 1991).

Growth of Microorganisms. Microorganisms growing in HVAC systems produce VOCs and aerosols that have well-known human health effects. Usually such growth is associated with water, either as standing pools, condensation on surfaces, or absorbed in hygroscopic materials. Virtually any part of a HVAC system can support active microbial growth if sufficient water is present. Standing water and very wet surfaces tend to support bacterial growth. Fungal growth predominates on dryer surfaces (Hugenholts and Fuerst 1992). Bacteria may survive dry environments and reappear after the reintroduction of water. Laboratory work on wallpaper substrates under varying moisture conditions indicates that fungal microcolonies can develop within a week on occasionally wet surfaces (Pasanen et al. 1992b). Similar growth would be expected for HVAC components.

Aerosolization of microorganisms from HVAC reservoirs can occur via air movement and turbulence, mechanical disturbance (e.g., duct cleaning devices, high pressure water or steam sprays), movement of the component (e.g., fans), droplet splash (standing water), and by discharge mechanisms that are intrinsic to many microorganisms, especially the fungi.

Cooling Coils. High concentrations of bioaerosols (spores of *Penicillium, Cladosporium, Aspergillus*, etc.) have been found downstream of cooling coils in many problem buildings, especially after agitation of the coils, spores were dislodged (Morey 1988, 1992). Hugenholtz and Fuerst (1992) present a scanning electron micrograph of a bacterial biofilm on a cooling coil surface. The rapidly moving air stream about the coils provides a suspension mechanism for the aerosols. Inadequate maintenance (e.g., cleaning) and poor filtration (allowing high concentrations of outdoor-source organic material to accumulate on the coils) contribute to this source.

Drain Pans, Drains, Traps, and Sumps. Standing water due to clogged condensate drains and traps in AHUs and other mechanical spaces is frequently noted in inspections as a potential IAQ problem (e.g., Ager and Tickner 1983, Downing and Bayer 1991, Trent 1992), and has been identified as potential source of microbial contamination. Although aerosolization of the contaminated water has not been identified or confirmed, droplet splash mechanisms and intrinsic discharge mechanisms in the yeasts commonly found in these environments (i.e., *Sporobolomyces, Itersonilia*) are sufficient to assume that aerosols are produced. Water in normally operating traps and sumps can be ejected and aerosolized under a high vacuum "pull-through" system as air rushes in the open drain line (Trent 1992). Contaminated condensate water can produce odors without aerosolization. McJilton et al. (1990), for example, found odors that were apparently caused by bacterial growth in condensate water in three buildings. Two VOCs (2-methyl propionic acid and 1-butoxy-2-propanol) were associated with the bacteria.

Filters. Case reports show that microbial contamination and amplification occur on filters in the presence of sufficient moisture. Being in the air stream, spores and other bioaerosols may be released. Microbial growth can deteriorate the filter media, decrease filtration efficiency, cause clogging, and decrease the filter's useful life. Bernstein (1983), for example, describes fungal contamination (primarily *Penicillium*) on filters and surrounding areas. Problems due to poor filter maintenance are described in other case reports (Acierno et al. 1985, Morey et al. 1987, Pasanen et al. 1991a). Rivers et al. (1992) measured VOCs emitted by pure bacterial strains isolated from organisms recovered from residential air filters. VOCs emitted by many of the cultures included ethanol, methyl mercaptan and dimethyldisulfide; other VOCs included methanol, trimethylamine, ethanol, acetone, methyl ethyl ketone, dimethyl disulfide, dimethyltrisulfide, indole, cresol, and phenol. The VOC composition and emission rates depended on the bacterial strains, the metabolic activity, and possibly the growth medium. Pasanen et al. (1991b) found that high (96%) relative humidity rapidly stimulated fungal growth on filters removed from office buildings.

Insulation. Some materials used to line HVAC components for thermal and acoustic purposes can support microbial growth in the presence of sufficient nutrients and moisture. Morey (1988; 1990b; 1992) and Morey and Williams (1991) identify porous fiber linings in air-handling units, ductwork and air terminal boxes as reservoirs and amplifiers of microorganisms. Both insulated and non-insulated surfaces near these water reservoirs may also become contaminated. Insulated surfaces may be less likely to allow condensation than metal surfaces. However, if the insulated surface is hygroscopic, or becomes dirty, contamination becomes likely at lower ambient water levels than is required for metal surfaces. Microbial problems are more likely in supply ducts during the cooling season, with relative humidities over 70 to 80%, when filters are missing, and with malfunctioning humidifiers. Removal and cleaning of contaminated insulation may aerosolize microbes (Morey 1992). Insulation may be resistant to sterilization, possibly due to embedded fungal material and adherent bacteria that recolonize the insulation (Morey 1988). New linings with impermeable surfaces may reduce the potential for colonization without compromising acoustical or insulating effectiveness. For example, Ahearn et al. (1992) show that rigid compressed fiberglass with a foil facing supported little microbial growth, while plastic-faced insulation was colonized by xerophilic fungi.

Duct Surfaces. Duct surfaces provide a reservoir and amplifier (if moistened) for fungi and bacteria. Duct cleaning and removal of contaminated materials (e.g., porous insulation) may also aerosolize biological contaminants (Morey 1992).

Plenums. Ceiling tiles, fireproofing materials, and fibrous insulation in plenums that become wet due to roof leaks, inadequate humidity control, etc., may support microbial growth (Morey 1988; Morey and Shattuck 1989; Morey 1990a).

Humidifiers and Evaporative Coolers. Microbial contamination and amplification may occur in water reservoirs and sumps of humidifiers and air washers that use recirculated water, and in standing reservoirs and stagnant water of cold water humidification systems (Liebert et al. 1983; Flaherty et al. 1984; Breif and Bernath 1988; Morey and Shattuck 1989; Morey 1992). Aerosolization is likely with cold water spray humidifiers and air washers. These systems have been associated with humidifier fever and hypersensitivity pneumonitis (Arnow et al. 1978; Fink et al. 1976; Rylander and Haglind 1984; Acierno et al. 1985; Hodgson et al. 1987). Aerosols may be transported past demisters or baffle plates (Ager and Tickner 1983; Flaherty et al. 1984). If excessive moisture is emitted from humidifiers due to leaks or other malfunctions, microbial growth may occur at downstream components, such as heat exchangers and duct linings. Banaszak et al. (1970) and Morey (1988) suggest respiratory and systemic symptoms have been caused by thermophilic actinomycetes in evaporative coolers using a cold water spray and city water. Ager and Tickner (1983) review problems associated with systems that store and recirculate water.

Cooling Towers. As is well known due to incidents of Legionnaires' Disease and Pontiac fever (e.g., Winn 1985), cooling tower water from the evaporative condenser may provide a site for microbial amplification and bioaerosol generation. Aerosols may escape demisters or baffle plates and enter HVAC systems with intakes nearby or downwind (Ager and Tickner 1983; Breif and Bernath 1988).

VOC Sinks. Potential sinks for VOCs and semivolatile compounds include filters, sound absorbers, and insulation materials (in addition to dust, as discussed above) (Levin and Moschandreas 1990). The few studies examining sink-source effects are mentioned previously under Dust. The potential sinks that are intrinsic to HVAC systems have not been studied.

Cleaning Compounds and Biocides. Detergent and chemical cleaning, and sterilization of HVAC surfaces can produce aerosols and VOCs, including toxic chlorine-containing and antimicrobial compounds (e.g., bleach, copper-8-quinolinolate, alcohols, phenols, aldehydes, and iodides (ACGIH 1989; Luoma et al. 1993). The U.S. EPA does not list any biocides as approved for use in ducts or humidification systems. A number of biocides are registered for use in cooling towers. However, cooling tower effluent is assumed not to enter the HVAC system and the occupied space. Deodorizers release VOCs when used on filters for the purpose of disguising odors (Downing and Bayer 1991).

Boiler Steam. Direct steam injection humidifiers routinely emit into the airstream hazardous steam conditioning anticorrosive agents (e.g., soluble nitrosated amines like morpholine) (National Research Council 1983; Morey and Shattuck 1989). Other chemicals used in these systems, but not normally during humidifier operation, include biocides, slimicides, oxygen-scavenging or filming chemicals, anti-corrosives, and pH control neutralizers (Halas 1991a; 1991b).

Design/Operational Effects on IAQ

Entrainment and Re-entrainment. Inadequate filtration may allow high levels of outdoor aerosols (fungi and bacteria) to enter the ventilation airstream. Excessively dirty or clogged filters reduce ventilation and thus increase concentrations of contaminants emitted by occupants and by building materials. If filters are missing, improperly installed (e.g., with gaps and air leakage between filters and the filter housing, or have low or unrated efficiency against fine particles, the airstream may contain high particulate concentrations (Ottney 1993). These particles can deposit in the HVAC system leading to problems discussed above, or may be transported directly to the occupied space.

Leaves, soil, vegetable matter, stagnant water, etc., near or in air intakes may allow the growth of fungi and bacteria that may subsequently enter the HVAC system (ACGIH 1989).

While some re-entrainment of exhaust air almost always occurs in any building with intakes and exhausts, special concerns include air intakes placed near or downwind from exhaust ducts, cooling towers, sanitary vents, idling vehicles, laboratory hood exhausts, and other emission sources (Ager and Tickner 1983; Godish 1986; Hughes and O'Brien 1986; Morey and Shattuck 1989; Burton 1990; Hodgson et al. 1991). These situations can be avoided given acceptable dilution factors, avoidance of the recirculation cavity, and sufficient stack exit velocities.

Rotary Heat Exchangers. Rotary heat exchangers may transfer VOCs from exhaust (relief) air to supply air. Several studies show significant VOC contributions (Hughes and O'Brien 1986; Ekberg 1991). Unfortunately, these studies did not specify the design and materials of the exchanger. Conversely, no pollutant transfer was found at a heat recovery wheel coated with a molecular sieve desiccant (Bayer and Downing 1991).

Building Pressurization. Insufficient building pressurization may increase the infiltration of contaminated air (Morey and Shattuck 1989; Morey 1990a). Such situations include infiltration of vehicular exhaust in parking decks below offices (Godish 1986; Hodgson et al. 1991), street-level carbon monoxide from traffic (Collett et al. 1991), and exhaust air from building combustion devices (e.g., furnaces). Building depressurization can also increase the transport of radon containing soil gas into a structure. Relationships between building depressurization and radon levels are reasonably well understood (e.g., Nazaroff et al. 1987; Mosely 1992), and mitigation measures have been extensively studied (Henschel 1988). Radon contamination and mitigation are beyond the scope of this review.

Transport. The conveyance of contaminated air in HVAC systems will occur in any building that has any degree of recirculation. Contaminant migration will also occur within and between rooms and floors if pressure imbalances exists (Hughes and O'Brien 1986). For example, Bloch (1985) shows the transport of measles in a physician's office; and Chang and Guo (1990) show transport of contaminant gases in a residence. Aerosols and VOCs may also be transported. Reynolds et al. (1990) show transport of fungi via the HVAC system or possibly by human activity in several homes and office buildings. Morey (1990a) mentions the need to avoid movement of contaminants between apartments by proper zoning or provision of separate ventilation systems. These problems can be avoided by providing local exhaust to source areas, e.g., reproduction areas, cafeterias, smoking areas, and by minimizing pressure imbalances.

Climate Control. In especially hot and humid climates, inadequate humidity control may result in microbial contamination on surfaces of building materials and possibly building contents. One case report indicates that high humidities softened and impaired the curing of carpet adhesives that then appeared to emit high levels of VOCs (Bayer and Downing 1992). While design temperatures were achieved in the hot and humid climate, the HVAC system was unable to remove excessive moisture from the air.

Ventilation and Air Exchange. Inadequate provision of outside air to interior spaces leads to unacceptable IAQ (e.g., Morey and Shattuck 1989; Wolter 1991; Persily 1993). Contributing factors may include purposely closed, inoperable and/or uncalibrated outside air dampers; insufficient air flow, especially during "pinch-down" of VAV systems; inadequate air distribution; low ventilation efficiency; entrainment and contaminant migration (as discussed above); and other circumstances. Air exchange rates have been found to be inversely proportional to carbon dioxide (CO_2) and some other pollutant levels, as expected (Persily 1993). However, several longitudinal studies in which exchange rates were altered have not provided the expected results with respect to odor, irritant and health outcomes or perceived IAQ. For example, in a 19 story office building at low outside air ventilation rates, higher ventilation rates increased the infiltration of outside air containing carbon monoxide from street level sources, indicating that building pressurization was insufficient (Collett et al. 1991). Menzies et al. (1993) found that increases in outside air ventilation over a narrow, high range (up to 50 cfm/person) did not decrease the incidence of sick building syndrome symptoms or of complaints reported by office workers. Secondary factors that may have confounded results in both studies include deficiencies in the monitoring instrumentation and monitoring approaches, the inability to characterize microenvironments, and unaccounted emission sources.

Cleaning. As mentioned earlier, duct cleaning may aerosolize biological contaminants found in ducts due to rapid air movement and turbulence, mechanical disturbance, and movement of components.

Control of microbial contamination involves limiting access to water, and rigorous maintenance of components that are necessarily wet. Access to small AHUs installed and sealed within building walls (Morey and Shattuck 1989), and the lack of access doors in large AHUs are common problems that prevent necessary maintenance.

SENSORY STUDIES

Several studies have apportioned contaminants to major classes of emission sources, including the HVAC system, using sensory measures. Using a sensory panel, Fanger et al. (1988) investigated 20 spaces in Copenhagen with occupants present, occupants absent, and with the occupants absent and the HVAC system turned off. Using the approach described by Equations (2) and (3), the estimated contribution of the HVAC system to the total perceived IAQ degradation varied from space to space but averaged 40%. The sensory measurements were not correlated with CO, CO_2, air exchange rate, or TVOC levels measured in the buildings. Using the same longitudinal technique, Pejtersen et al. (1991) studied 10 kindergarten classrooms, obtaining comparable results. However the ventilation systems produced a higher contribution (in olf/m^2 floor area) than found in offices and assembly halls. Based on CO_2 measurements, several schools were poorly ventilated. In a variation of this approach, Pejtersen et al. (1993) used a sensory panel, CO, and CO_2 measurements to apportion the perceived IAQ degradation to three source categories: occupants; smoking; and building materials and the ventilation system (combined). CO served as a surrogate for cigarette smoking, and CO_2 for bioeffluents. The non-cigarette and non-bioeffluent component is attributed to the materials and ventilation system. In nine buildings, 62% of the olf load is attributable to the building and ventilation system.

These studies indicate the potential importance of the HVAC system as a contaminant source. Unfortunately, culpable HVAC components are not identified. Additionally, it is unclear whether results reflect intrinsic emission sources or those resulting from contamination, and study designs may have determined whether sorption or desorption processes were emphasized. Finally, the relationship of the sensory responses to physical-chemical measures is unclear. In particular, nonlinearity and thresholds of sensory responses should be taken into account when apportioning sources quantitatively.

DISCUSSION

This paper has focused on contaminant emission sources and has highlighted sources and problems in HVAC systems. Few studies focus on the acceptable IAQ that is provided by HVAC systems in many or most buildings. Also, all of the longitudinal or cross-sectional health outcome studies have focused on problem building syndrome. It is probably true that the environment in most mechanically ventilated buildings is protective for people who are sensitive to the common outdoor allergens (e.g., pollens and many kinds of fungus spores). Ambient fungus spore levels in mechanically ventilated buildings appear to be considerably lower than those in outdoor air, or in naturally ventilated homes.

Based on the available literature, however, many HVAC components can act as direct or indirect sources of particles and/or VOCs which may affect IAQ under some conditions. Several components appear fairly frequently in the literature, and there is broad agreement regarding their significance. Prominent among these is biological growth and bioaerosol generation in the presence of moisture provided by air washers and other recirculating water systems; poor control of humidity; poorly designed humidifying systems; poorly maintained cooling coils and drip pans, etc. These problems appear to be exacerbated by dust accumulation, and by the presence of fibrous insulation. A number of studies describe entrainment, migration, and infiltration of indoor and outdoor contaminants that are distributed to indoor spaces by the HVAC system. The importance of good design and operation of HVAC systems, including the appropriate placement and maintenance of air intakes, building pressurization, and local exhaust in source areas, is also well accepted. More limited data implicate dust (resulting from inadequate filtration and maintenance of filters) as a sink and secondary source for VOCs. Evidence is inconclusive or inconsistent for the role of adhesives, coatings, sealants, drain pans, sumps, rotary heat recovery wheels, and plenums as primary sources for air pollutants.

Important Gaps in Available Data

We have found no single study (or collection of studies) of HVAC emission sources that was comprehensive, used robust physical-chemical measurements, and examined and isolated pollutant contributions from major HVAC components. This review has relied on case reports undertaken in problem buildings. These limitations have led to a number of important gaps in our knowledge:

1. The frequency with which various HVAC-related problems occur cannot be estimated.
2. With the exception of a few studies examining VOCs, pollutant emission rates have not been quantified, and thus the contribution of HVAC systems and components to overall IAQ has not been established.
3. The temporal and spatial variability of emissions has not been demonstrated.
4. The relationship between bulk samples of water, dust, or solid materials and the quality of delivered air is uncertain.
5. No studies have evaluated the efficacy of preventative measures regarding microbial colonization or VOC sink-source relationships.
6. The relationship between laboratory tests and building studies has not been verified.
7. In general, the uncertainty of results has not been characterized, either internally (e.g., using replicates within a study) or externally (e.g., using intercomparisons across studies), thus it is difficult to generalize many findings.

8. The trade-offs between preventative maintenance actions (e.g., minimization of biological growth and dust accumulation) and the impacts of cleaning, sterilization, and other remediation procedures are unknown.

Interpretation of Available Studies

As discussed previously, most of the literature is qualitative and consists of case reports. Such studies are useful as they identify potential sources. However, several factors must be addressed before generalizations can be made from this literature.

A key issue concerns the comparability, completeness, and relevance of the contaminant measurements obtained in the studies. For airborne particles, contaminant measurements include total and size-specific mass concentrations, gross number concentrations (using optical particle counters), speciated concentrations (e.g., counts of culturable microorganisms), and dust accumulation rates. Often, bulk sampling from reservoirs is used in lieu of air sampling, especially for microbial agents, with no evidence presented as to the representativeness of these methods. For VOCs, contaminant measurements include total and speciated VOCs recovered and analyzed by a variety of methods which may not be comparable. Sensory panels have provided information of yet a different nature. In most cases, alternate measurement approaches have not been evaluated or cross-validated, nor have standardized approaches been used.

A second factor is the timing and duration of measurements. The short monitoring periods that are typically mandated by the case nature of nearly all studies may not provide representative results due to effects of changing ambient conditions (e.g., humidity, air velocities, building loads, and other dynamic factors) that may alter emissions. For example, spore release rates depend on humidity and air velocity (Pasanen et al. 1991b) as well as the (finite) number of spores available for dispersal. To accurately evaluate emission rates for a specific case of fungus contamination requires the collection of (probably) hundreds of short term (minutes) samples collected over a long period (months) of time. Interpretation of the "snapshot" data provided in virtually all of the literature is problematic. For VOCs, the timing of measurements may reflect sorption or desorption periods with very different results. Results also may differ by season and HVAC operation mode (e.g., heating versus cooling, system start-up versus constant operation, etc.).

A third factor that makes interpretation of the existing literature difficult is the absence of controls for outdoor pollutants, and for smoking. Most reported studies have been done in urban areas, yet few studies examined outdoor pollutant levels. Smoking appears to have influenced outcomes in several studies. The current trend to limit smoking in indoor environments makes it mandatory that any study of HVAC system components as sources control for smoking, or that such studies be done in non-smoking environments.

Finally, although it is clear that HVAC components can release potential air pollutants, either intrinsically or as the result of contamination, it has not been clearly demonstrated that these sources contribute significantly to pollutant levels in indoor air. For example, the presence of a biologically-contaminated site or reservoir (e.g., a water sump or drain pan) may not constitute a significant HVAC emission source for bioaerosols. Likewise, high levels of dust (including biological particles) found deposited in ducts, air handling units, etc., do not constitute a particulate source unless the particles are reentrained and transported to the occupied space.

Recommendations

In any characterization study, decisions regarding overall study goals and data quality objectives must be made prior to the development of the sampling and analysis strategy. The following strategies are formulated with the primary goal of accurate quantification of emission sources in typical existing HVAC systems. Cost-effectiveness is a secondary goal.

For VOCs, a combination of *in situ* system and component studies, in conjunction with laboratory chamber tests, seems effective and comprehensive. The chamber studies confirm the VOC composition and provide qualitative estimates of emission rates; the *in situ* studies provide more representative and hopefully quantitative information under operating conditions. *In situ* component studies may indicate emission rates from specific sources, while system studies show the cumulative impact. In most buildings, such sampling appears feasible, although it will be practical to test only a fraction of the HVAC system, e.g. some supply and return ducts. Obtaining the necessary analytic precision and the temporal and spatial representativeness in the *in situ* tests is the major challenge. Actions that increase concentration increments across HVAC components will improve accuracy. This might include, for example, economizer mode (to minimize recirculation and assuming that concentrations in outside air are low), reduction or removal of internal building sources (e.g., monitor during unoccupied periods), and sampling during periods of low outdoor concentrations of the pollutants of interest. VOC sampling and analysis strategies should attempt to separate sorption and desorption processes that are anticipated to significantly affect apparent VOC emissions. Thus, monitoring should be performed both before and after the onset of high concentrations produced by the sum of building and outdoor emission sources. Continuous (or very frequent) monitoring may be needed to determine VOC patterns and to identify representative monitoring periods. Detailed test plans, including QA/QC, should be developed prior to sampling activity.

For particles (including bioaerosols), the sampling strategy is greatly influenced by restrictions in available measurement technology. The ability to collect representative and accurate samples is limited by changing duct velocities (especially in variable air volume systems), the range of particle sizes encountered, and typical HVAC configurations. No commercially available sampler will remain isokinetic in the constantly changing velocities and turbulence of an operating ventilation system. The errors that are introduced are particle size-specific and cannot be reliably predicted in any routine way. The use of optical particle counting and sizing methods may circumvent many sampling problems. Unfortunately, these methods do not allow chemical analysis of particles. With the technology that is currently practical for use in building investigations, the accuracy of most *in situ* particulate measurements will be compromised, leading to largely qualitative results.

A further problem has been mentioned with respect to evaluating emission rates of biological particles from active growth. Fungus spores, in particular, are produced in batches under conditions that do not necessarily favor particle release. Spores are often released in mass under specific conditions, and over very short periods of time. Capturing the peak of release is statistically unlikely given the relatively short sampling times mandated by the commercially available culture plate sampling devices. Thus, false negatives (or falsely low emission rates) are likely for these particles.

Until devices are available that allow isokinetic, time-discriminated measurement of particles in operating HVAC systems, we suggest that bulk samples be collected to identify potential contamination sites, and that air samples be collected in occupied spaces to document that identified agents actually are released from the system. Such studies should be carefully designed to include a range of HVAC operating conditions (e.g., immediately after a weekend shut-down, immediately before start-up, immediately after start-up, periodically during a week of building operation, etc.). They should include controls for any other potential sources of the agent, including outdoor air. In addition, air samples can be collected immediately downstream from suspected reservoirs within seconds of turning the HVAC system off. Small particles should remain entrained under these circumstances, and the turbulence that might occur at this instant might create a useful "worst case" situation. Such samples can be collected before and during mechanical agitation of the reservoir, although these data are difficult to interpret with respect to actual HVAC operating conditions.

For a few HVAC components, case-control techniques could reduce some of the uncertainties arising from measurement errors and environmental factors. These techniques are applicable to both particulate and VOC emissions for those HVAC components that can be easily altered in controlled interventions. With filters, for example, different filter types or clean versus dirty filters could be compared in adjacent, similar buildings, or in a single building with more than one ventilation system. Emissions could be monitored at both sites under both conditions.

CONCLUSION

This review has identified numerous sources and problems related to indoor air contaminants and HVAC systems. These have been characterized as intrinsic emission sources, emission sources resulting from contamination, and HVAC design and operational impacts on IAQ. Many of the sources and HVAC system deficiencies have the potential to critically affect IAQ. However, limitations in the available studies do not permit quantitative estimates of the frequency or the intensity of specific sources. We have also evaluated approaches to characterizing HVAC emission sources. The various measurement approaches provide different and complementary information. The use of several approaches is recommended to provide the most reliable information.

ACKNOWLEDGEMENTS

We appreciate suggestions by M. Luoma, R. Kulp, L. Sparks, B. Tichenor, and the editorial board of *HVAC&R Research*. This work was performed with the financial support of ASHRAE and under the sponsorship of the Environmental Health Subcommittee (662-TRP).

REFERENCES

ACGIH. 1989. *Guidelines for the assessment of bioaerosols in the indoor environment*. Cincinnati, OH: American Conference of Governmental Industrial Hygienists.

Acierno, L.J., J.S. Lytle, and M.H. Sweeny. 1985. Acute hypersensitivity pnuemonitis related to forced air systems—A review of selected literature and a commentary on recognition and prevention. *J. Env. Health* 48(3): 138-141.

Ager, B., and J.A. Tickner. 1983. The control of microbiological hazards associated with air-conditioning and ventilation systems. *Ann. Occup. Hyg.* 27(4): 341-358.

Ahearn, D.G., D.L. Price, R.B. Simmons, and S.A. Crow. 1992. Colonization studies of various HVAC insulation materials. In *Proceedings of IAQ '92 Environments for People*, pp. 101-105. Atlanta: ASHRAE.

Anom. 1991. Duct cleaning—Troubleshooting foul air. *Air Cond., Heating & Refrigeration News*, Oct. 7: 32.

Arnow, P.M., J.N. Fink, and D.P. Schluete. 1978. Early detection of hypersensisitivity pneumonitis in office workers. *Am. J. Med.* 64: 236-243.

ASTM. 1991. *ASTM Standard 5116-90, Standard guide for small-scale environmental chamber determinations of organic emissions from indoor materials/products*. Philadelphia, PA: American Society for Testing and Materials.

Banaszak, E.F., W.H. Thiede, and J.N. Fink. 1970. Hypersensitivity pneumonitis due to contamination of an air conditioner. *New Eng. J. Med.* 283(6): 271-276.

Bayer, C.W., and C.C. Downing. 1991. Does a total energy recovery system provide a healthier indoor environment? In *Proceedings of IAQ '91 Healthy Buildings*, pp. 74-76. Atlanta: ASHRAE.

Bayer, C.W., and C.C. Downing. 1992. Indoor conditions in schools with insufficient humidity control. In *Proceedings of IAQ '92 Environments for People*, pp. 115-118. Atlanta: ASHRAE.

Bernstein, R.S. 1983. Exposures to respirable, airborne *penicillium* from a contaminated ventilation system: Clinical, environmental and epidemiological aspects. *Am. Ind. Hyg. Assoc. J.* 44(3): 161-169.

Bloch, A.B. 1985. Measles outbreak in a pediatric practice: Airborne transmission in an office setting. *Pediatrics* 75(4): 676-683.

Breif, R.S., and T. Bernath. 1988. Indoor pollution: Guidelines for prevention and control of microbiological respiratory hazards associated with air conditioning and ventilation systems. *Appl. Ind. Hyg. Assoc.* 3(1): 5-10.

Burge S., A. Hedge, S. Wilson, J.H. Bass, and A. Robertson. 1987. Sick building syndrome: A study of 4373 office workers. *Ann. Occup. Hyg.* 31: 493-504.

Burrell, R. 1991. Microbiological agents as health risks in indoor air. *Env. Health Persp.* 95: 29-34.

Burton, D.J. 1990. Re-entrainment of building's exhaust air creates complex engineering problem. *Occup. Health Safety:* 36-38.

Chang, J.S., and Z. Guo. 1990. The effects of building features on indoor air and pollutant movements. In *Proceedings of IAQ '90*, pp. 67-73. Atlanta: ASHRAE.

Collett, C.W., J.A. Ventresca, and S. Turner. 1991. The impact of increased ventilation on indoor air quality. In *Proceedings of IAQ '91 Healthy Buildings*, pp. 97-100. Atlanta: ASHRAE.

Crandall, M.S. 1987. NIOSH indoor air quality investigations: 1971 through 1987. In *Proceedings, Air Pollution Control Association Annual Meeting*. Pittsburgh, PA: Air and Waste Management Association.

Downing, C.C., and C.W. Bayer. 1991. Operation and maintenance for quality indoor air. In *Proceedings of IAQ '91 Healthy Buildings*, pp. 372-374. Atlanta: ASHRAE.

Ekberg, L.E. 1991. Indoor air quality in a new office building. In *Proceedings of IAQ '91 Healthy Buildings*, pp. 125-127. Atlanta: ASHRAE.

Fanger, P.O., J. Lauridsen, P. Bluyssen, and P.G. Clausen. 1988. Air pollution sources in offices and assembly halls quantified by the olf unit. *Energy and Buildings* 12: 7-19.

Fink, J.N, E.F. Banaszak, and J.J. Baroriak. 1976. Lung disease from forced air systems. *Clin. Notes on Respiratory Dis.* 84(4): 406-413.

Flaherty, D.K., F.H. Deck, and J. Cooper. 1984. Bacterial endotoxin isolated from a water spray air humidification system as a putative agent of occupation-related lung disease. *Infection and Immunity* 43(1): 206-212.

Franke, J.E., and R.A. Wadden. 1987. Indoor contaminant emission rates characterized by source activity factors. *Environ. Sci. Technol.* 21: 41-45.

Godish, T. 1986. Indoor air pollution in offices and other non-residential buildings. *J. Environ. Health* 48(4): 190-195.

Halas, J.J. 1991a. Reflections on steam-humidified room air, part 1. *Engin. Systems* (Jan/Feb.): 98-100.

Halas, J.J. 1991b. Reflections on steam-humidified room air, part 2. *Engin. Systems* (March): 72-75.

Henschel, D.B. 1988. *Radon reduction techniques for detached houses. Technical Guidance*, 2nd ed. EPA/625/5-87/019 (NTIS PB88-184908). Research Triangle Park, NC: Air and Energy Engineering Research Laboratory, U.S. Environmental Protection Agency.

Hodgson, A.T., J.M. Daisey, and R.A. Grot. 1991. Sources and source strengths of volatile organic compounds in a new office building. *J. Air and Waste Manage. Assoc.* 41: 1461-1468.

Hodgson, M.J., P.R. Morey, and J.S. Simon. 1987. An outbreak of recurrent acute and chronic hypersensitivity pneumonitis in office workers. *Am. J. Epidemiol.* 125(4): 631-638.

Hugenholtz, P., and J.A. Fuerst. 1992. Heterotrophic bacteria in an air handling system. *Appl. Environ. Microbio.* 58(12): 3914-3920.

Hughes, R.T., and D.M. O'Brien. 1986. Evaluation of building ventilation systems. *Am. Ind. Hyg. J.* 47(4): 207-213.

Hujanen, M., O. Seppanen, and P. Pasanen. 1991. Odor emissions from the used filters of air handling units. In *Proceedings of IAQ '91 Healthy Buildings*, pp. 329-333. Atlanta: ASHRAE.

Kirkbride, J., H.K. Lee, and C. Moore. 1990. Health and Welfare: Canada's experience in indoor air quality investigations. In *Proceedings of Indoor Air '90*.

Kjaer, U.D., and P.A. Nielsen. 1993. Adsorption studies on dust samples from the indoor environment. In *Proceedings of Indoor Air '93*, vol. 2: 579-584.

Krzyanowski, M.E. 1992. Use of airborne particle counting to evaluate indoor air quality for remediation and control. In *IAQ '92 Environments for People*, pp. 289-299. Atlanta: ASHRAE.

Laatikainen, T., P. Pasanen, L. Korhonen, A. Nevalainen, and J. Ruuskanen. 1991. Methods for evaluating dust accumulation in ventilation ducts. In *Proceedings of IAQ '91 Healthy Buildings*, pp. 379-382. Atlanta: ASHRAE.

Leeds, L.W. 1968. *Lectures on ventilation at Franklin Institute, 1866-67*, pp. 8-9. New York: John Wiley and Sons.

Leovic, K.W., J.B. White, and C. Sarsony. 1993. EPA's indoor air/pollution prevention workshop. Presented at the *86th Annual Air and Waste Manage. Assoc. Meeting*. Pittsburgh, PA: Air and Waste Management Association.

Levin, H., and D. Moschandreas. 1990. Source assessment. In *Proceedings of IAQ '90*, pp. 461-462. Atlanta: ASHRAE.

Liebert, C.A., M.A. Hood, P.A. Winter, and F.L. Singleton. 1983. Observations on biofilm formation in industrial air-cooling units. *Devel. Ind. Microbio.* 24: 508-517.

Luoma, M., A.L. Pasanen, P. Pasanen, and Y. Fan. 1993. Duct cleaning—A literature survey. *AIVC Air Infiltration Rev.* 14(4): 1-5.

McClunney, R.J. 1987. The role of building construction and ventilation in indoor air pollution. *N.Y. State. J. Med.* 87(4): 203-209.

McJilton, C.E., S.J. Reynolds, S.K. Streifel, and R.L. Pearson. 1990. Bacteria and indoor odor problems—Three case studies. *Am. Ind. Hyg. Assoc.* 51: 545-549.

Menzies, R., R. Tamblyn, J.P. Farant, J. Hanley, F. Nunes, and R. Tamblyn. 1993. The effect of varying levels of outdoor-air supply on the symptoms of sick building syndrome. *New Eng. J. Med.* 12: 821-827.

Molhave, L., and M. Thorsen 1991. A model for investigations of ventilation systems as sources for volatile organic compounds in indoor climates. *Atmos. Environ.* 25A(2): 241-249.

Morey, P.R. 1988. Microorganisms in buildings and HVAC systems: A summary of 21 environmental studies. In *Proceedings of IAQ '88 Engineering Solutions to Indoor Air Problems*, pp. 10-24. Atlanta: ASHRAE.

Morey, P.R. 1990a. Internal HVAC pollution, Pilot study on indoor air quality. Report on Meeting Held in Sainte-Aldele, Quebec, Canada, Aug. 6-8.

Morey, P.R. 1990b. Porous insulation in buildings—A potential source of microorganisms. In *Proceedings of IAQ '90*. Atlanta: ASHRAE.

Morey, P.R. 1992. Microbiological contamination in buildings: Precautions during remediation activities. In *Proceedings of IAQ '92 Environments for People*, pp. 94-100. Atlanta: ASHRAE.

Morey, P.R., and D.E. Shattuck. 1989. Role of ventilation in the causation of building-associated illness. *Occup. Med. State of Art Revs.* 4(4): 625-642.

Morey, P.R., and C.M. Williams. 1991. Is porous insulation inside an HVAC system compatible with a healthy building? In *Proceedings of IAQ '91 Healthy Buildings*, pp. 128-135. Atlanta: ASHRAE.

Morey, P.R., W.G. Jones, J.L. Clere, and W.G. Sorenson. 1987. Studies of sources of airborne microorganisms and on indoor air quality in a large office building. In *Proceedings of IAQ '86, Managing Indoor Air for Health and Energy Conservation*, pp. 20-23. Atlanta: ASHRAE.

Moseley, C. 1990. Indoor air quality problems, a proactive approach for new or renovated buildings. *J. Environ. Health* 53(3): 19-23.

Mosely, R.B. 1992. A simple model for describing radon migration and entry into houses. *Indoor radon and lung cancer: Reality or myth?* , ed. F.T. Cross, pp. 339-356. Columbus, OH: Batelle Press.

National Research Council. 1983. *An assessment of the health risks of morpholine and dimethylaminoethanol.* Washington, DC: National Academy Press.

Nazaroff, W.W., S.R. Lewis, S.M. Doyle, B.A. Moed, and A.V. Nero. 1987. Experiments on pollutant transport from soil into residential basements by pressure-driven airflow. *Environ. Sci. Tech.* 21: 459-466.

Nyman, E., and N. Sandstrom. 1991. *Mikroorgnismer i ventilations sytem*, 38 pp. R45. Byggforskningsrdet: Sweden (in Swedish).

Ottney, T.C. 1993. Particle management for HVAC systems. *ASHRAE Journal* 35(7): 26-34.

Pasanen, A., H. Heinonen-Tanksi, P. Kalliokoski, and M.J. Jantunen. 1992b. Fungal microcolonies on indoor surfaces—An explanation for the base-level fungal spore counts in indoor air. *Atmos. Environ.* 26B(1): 117-120.

Pasanen, A.L., P. Pasanen, M.J. Jantunen, and P. Kalliokoski. 1991b. Significance of air humidity and air velocity for fungal spore release into the air. *Atmos. Environ.* 25A(2): 459-462.

Pasanen, P., A. Nevalainen, J. Ruuskanen, and P. Kalliokoski. 1992a. The composition and location of dust settled in supply air ducts. *13th AIVC Conference on Ventilation for Energy Efficiency and Optimum Air Quality*. Nice, France, Sept. 15-18.

Pasanen, P., M. Hejanen, A.L. Pasanen, A. Nevalainen, and J. Ruuskanen. 1991a. Criteria for changing ventilation filters. In *Proceedings of IAQ '91 Healthy Buildings*, pp. 383-385. Atlanta: ASHRAE.

Pejtersen, J. et al., 1991. Air pollution sources in kindergartens. In *Proceedings of IAQ '91 Healthy Buildings*, pp. 221-224. Atlanta: ASHRAE.

Pejtersen, J., G. Clausen, and O. Fanger. 1992. Olf och energi—Fase 2: Olf-vaerdier for og efter rensning af ventilationsanlaeg. Draft (in Danish), 43 pp. Denmark: Laboratory of Heating and Air Conditioning, Technical University of Denmark.

Pejtersen, J., L. Oie, S. Skar, G. Clausen, and P.O. Fanger. 1993. A simple method to determine the olf load in a building. In *Proceedings of Indoor Air '93*. Atlanta: ASHRAE.

Persily, A.K. 1993. Ventilation, carbon dioxide, and *ASHRAE Standard 62-1989*. *ASHRAE Journal* 35(7): 40-44.

Price, B., and K.S. Crump. 1992. Exposure inferences from airborne asbestos measurements in buildings. In *Proceedings of IAQ '92 Environments for People*, pp. 63-68. Atlanta: ASHRAE.

Reynolds, S.J., A.J. Streifel, and C.E. McJilton. 1990. Elevated airborne concentrations of fungi in residential and office environments. *Am. Ind. Hyg. Assoc. J.* 51(11): 601-604.

Rivers, J.C., J.D. Pleil, and R.W. Wiener. 1992. Detection and characterization of volatile organic compounds produced by indoor air bacteria. *J. Exp. Anal. Env. Epid.*, Suppl. 1: 177-188.

Rothenberg, S.J., P.A. Nagy, J.A. Pickrell, and C.H. Hobbs. 1989. Surface area, adsorption, and desorption studies on indoor dust samples. *Am. Ind. Hyg. Assoc. J.* 50(1): 15-23.

Rylander, R., and P. Haglind. 1984. Airborne Endotoxins and Humidifier Diseases. *Clin. Allergy* 14: 109-112.

Shumate, M.W., and J.E. Wilhelm. 1991. Air filtration media—Evaluations of fiber shedding characteristics under laboratory conditions and in commercial installations. In *Proceedings of IAQ '91 Healthy Buildings*, pp. 337-334. Atlanta: ASHRAE.

Tichenor, B.A. 1989. Indoor air sources: Using small environmental test chambers to characterize organic emissions from indoor materials and products. EPA-600/8-89-074 (NTIS PB90-110131). Research Triangle Park, NC: Air and Energy Engineering Research Laboratory, U.S. Environmental Protection Agency.

Tichenor, B.A., and M.A. Mason. 1988. Organic emissions from consumer products and building materials to the indoor environment. *J. Air Pol. Control. Assoc.* 38: 264-268.

Trent, W. 1992. IAQ and HVAC—Some major problems and a practical remedy. *Air Cond. Heating & Refrigeration News* (Oct. 19): 2-5.

Viner, A.S., P.A. Lawless, D.S. Ensor, and L.E. Sparks. 1992. Ozone generation in DC energized electrostatic precipitators. *IEEE Trans. Indus. Appl.* 28(3): 504-512.

Wilkins, C.K., P. Wolkoff, F. Gyntelberg, P. Skov, and O.I. Valbjorn. 1993. Characterization of office dust by VOC and TVOC release—Identification of potential VOCs by principal least squares analysis. In *Proceedings of Indoor Air '93*, vol 4: 37-42.

Winn, W. 1985. *Legionella* and Legionnaires' disease: a review with emphasis on environmental studies and laboratory diagnosis. *CRC Crit. Rev. Clin. Lab. Sci.* 21(40): 323-338.

Wolter, R. 1991. Proper ventilation improves indoor air quality. *Safety and Health* (June): 36-39.

Woods, J.E., 1983. Sources of indoor air contaminants. *ASHRAE Transactions* 89(1B): 462-497.

Notice

Although the information in this article has been funded in part by the United States Environmental Protection Agency under Cooperative Agreement CR815391-01 to the American Society of Heating, Refrigerating and Air-Conditioning Engineers, it does not necessarily reflect the views of the Agency and no official endorsement should be inferred.