Buildings Operations and ETS Exposure

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Mechanical systems are used in buildings to provide conditioned air, dissipate thermal loads, dilute contaminants, and maintain pressure differences. The characteristics of these systems and their operations have implications for the exposures of workers to environmental tobacco smoke (ETS) and for the control of these exposures. This review describes the general features of building ventilation systems and the efficacy of ventilation for controlling contaminant concentrations. Ventilation can reduce the concentration of ETS through dilution, but central heating, ventilating, and air conditioning (HVAC) can also move air throughout a building that has been contaminated by ETS. An understanding of HVAC systems is needed to develop models for exposures of workers to ETS. — Environ Health Perspect 107(Suppl 2):313–317 (1999). http://ehpnet1.niehs.nih.gov/docs/1999/Suppl-2/313-317spengler/abstract.html

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Most buildings are designed to provide functional space for various human activities, with ventilation requirements depending upon the anticipated use of the space. The overall goal is to provide a comfortable and safe level of indoor air quality. Mechanical systems are intended to provide conditioned air, dissipate thermal loads, dilute contaminants, and maintain pressure differences. Ventilation is accomplished through a variety of strategies: air is conditioned, mixed, and distributed by large central heating, ventilation, and air conditioning (HVAC) systems or conditioned locally with unitary systems. The characteristics of these systems and their operations have implications for exposures to environmental tobacco smoke (ETS) in the workplace and for the control of these exposures. Mechanical systems can dilute ETS by ventilation, yet they can also distribute components of ETS throughout the building by recirculation and thus contribute to occupants' exposures.

Most Americans work in buildings classified as office space. This unifying classification does not, however, reflect the great variety of ventilation systems, office equipment, tasks, materials, and furnishings, among other factors, that define the working environment. Employees' productivity is a complex interplay of ability, motivation, organization, technology, and the environmental conditions of the workplace; and ventilation systems have been key to maximizing worker comfort. The effects of thermal conditions on work productivity have long been considered in building design and operations, as has air exchange to control odor and infection (1,2). More recently, comfort and symptom control have become dominant considerations.

Tobacco smoke contains irritant gases, vapors, and particulate matter. Laboratory and field studies confirm that exposure to ETS can irritate the eyes and upper and lower airways and generally annoy the exposed nonsmoker. For more than a decade, studies have shown general and widespread dissatisfaction with cigarette smoke in the workplace, restaurants, and commercial airplanes (3,4). The ventilation guidelines of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), 62-1989 (5), are based on a maximum of 20% dissatisfaction among visitors to spaces. Ventilation tests in chambers under controlled conditions show clear relationships between the amount of cigarettes smoked, odor responses, and dissatisfaction with the quality of the air as experienced by visitors sensing the air from a sampling port in the duct system outside the chamber (6). Extrapolating from these experiments, ASHRAE 62-1989 sets a minimum ventilation rate at 15 ft3 per minute (cfm) per occupant. A higher rate of 20 cfm per occupant is specified for offices, conference rooms, dining rooms, and lobbies. In designated smoking lounges, 60 cfm per person is necessary to reduce irritation, whereas bars and casinos require 30 cfm per person.

Perhaps the ASHRAE 62-1989 guidelines need further explanation regarding irritation from ETS. Experimental data imply that 4000 ft3 is needed to dilute the emissions of one cigarette to levels at which only 20% of nonsmokers would be dissatisfied. If we assume that only 10% of the occupants in an office building are smokers at any given time, then the ventilation requirement to satisfy 80% of the occupants would have to be 53 cfm per person. The ASHRAE 62-1989 guideline of 20 cfm per occupant in office buildings necessarily implies prohibition on indoor smoking if the goal of 20% satisfaction is to be achieved.

Building Ventilation Systems

Thermal conditioning of ventilation air became manageable in 1903 by the widespread application of Willis Carrier's unvented air conditioning system. This "Apparatus for Treating Air" used water spray for conditioning, either heating the water for humidification or cooling the water for dehumidification. Carrier was ridiculed for proposing that spray water could be used for dehumidification. As a result, the first apparatus sold, in 1904, was only used for washing air. It was not until 1906, after independent tests were conducted, that a textile manufacturer installed the apparatus as the first central humidifying system. And it was not until 1911 that the principles were accepted by the profession for humidity control (7).

Yaglou's 1936 investigations (8) on ventilation and perceived evaluation of acceptance, along with other research into thermal environmental conditions, have led to guidance on the design and operation of building ventilation systems (9). These guidelines specify thermal and humidity conditions that will create a comfortable environment for occupants. The ranges of temperature and relative humidity are broad in order to encompass gender differences in clothing and sensory
response and slight shifts between summer and winter seasons. The comfort guidelines are not really optimized for performance and they do not consider the need to ventilate (dilute) for odor or contaminant control. The ASHRAE 62-1989 standards are the consensus guidelines necessary for ventilation to achieve acceptable indoor air quality. These standards, which have become municipal codes, specify the minimum amount of outside air to be brought into buildings and spaces of various types.

HVAC systems provide heating, ventilation, and air conditioning of indoor spaces. The HVAC system in buildings may comprise air handling units of various sizes and complexities that might filter and condition air supplied to the building. Components of air handling units (AHUs) include fans, filters, cooling coils, and heat exchangers. Conditioned air can be ducted to separate areas within the building. Figure 1 presents schematically a typical AHU configured for a hospital requiring enhanced filtration.

Before the energy concerns of the 1970s, central AHUs were constant air volume systems. The percentage of outside air might vary by damper settings but the supply air remained constant to rooms. Thermal conditions were met by reheat boxes or by modulating the amount of warm and cool air in a two-duct system. Beginning with the office building boom of the 1980s, variable air volume (VAV) air handling systems were introduced. As seen in Figure 2, the VAV system utilizes the internal heat load to warm spaces. Although VAV systems save energy, the amount of fresh air delivered to a room is determined by thermal requirements and not necessarily by the need to dilute odors and contaminants. Once thermal conditions are met, the VAV system reduces or shuts off ventilation air. Over recent decades, indoor air quality (IAQ) complaints have become more prevalent as VAV systems, sealed buildings, and greater use of synthetic materials became the construction norm.

HVAC systems also come as unitary fan-coil or unit ventilators. Unitary systems, as shown in Figure 3, are common for ventilation in schools. Often located along the perimeter wall, these units mix air from the room with outside air drawn in locally. Unit ventilators are operated individually and typically serve a single ventilation zone such as a classroom or office. Combined AHU and reverse-cycle heat pumps have become popular for generic speculation-built office space. Typically, a ceiling-mounted heat pump system will mix and condition air in localized areas such as a few adjacent offices, a conference room, or a reception area. Outside air may be ducted to the heat pump units and mixed in varying proportions with the building air. With less expensive construction, unconditioned air is forced into the ceiling plenum above a dropped ceiling, where it is mixed with “used” air. Heat pump systems positioned throughout the ceiling space draw in premixed air and heat or cool it to the conditions specified by the thermostat.

Unitary systems may have dampers, fans, cooling and heating coils, and filters. These devices give flexibility to office design, as they can be placed conveniently to deliver conditioned air to zones that might have different thermal requirements. Typically unitary systems are located at the perimeter. There are, however, several potential IAQ problems associated with the perimeter terminal unit concept. It is more difficult to maintain control of thermal and ventilation conditions. Differences in thermal loads and comfort settings can lead to pressure imbalances and complaints among occupants, even those sharing the same unit in adjacent but separate spaces. If the ceiling plenum is used as supply air or return air, problems can occur, as this space is rarely cleaned and often is strewn with cables and other obstructions to air flow. Finished construction of internal walls typically does not extend above the ceiling. Breaches as well as cable and pipe chases allow unplanned pathways for air, moisture, and contaminants. The effects may extend over several floors.

Reversing a 20-year trend, buildings are now designed to have windows that open. Employees with access to windows that open have a sense of control over their environment and will use outside air to moderate their local area. Quite high dilution rates can be obtained, but windows cannot be relied upon to comply with ventilation requirements of building codes.

Displacement ventilation systems are beginning to appear in the United States. In Europe, particularly in the Nordic countries, buildings have been designed with this system for several years. The concept of

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**Figure 1.** Air handling unit. Note: Hospital HVAC systems must utilize 90% final filters and 30% filters.

**Figure 2.** Variable air volume (VAV) box: shuts down until space builds up heat from sources within space.

**Figure 3.** Unit ventilator or fan coil unit.
displacement ventilation systems is to introduce conditioned air that replaces used air in the room. Typically these systems are designed to use 100% outside air that may be reconditioned using heat exchangers. In contrast to the displacement system, the conventional HVAC system modifies conditioned air by vigorously mixing it with room air. Displacement systems deliver air closer to the desired thermal conditions at lower velocities at floor level. Stale room air is drawn out at ceiling height. Although total delivered air is less and requires smaller ducts, it must be delivered through larger diffusers. In general, source reduction and changes in interior design will lead to greater acceptance of the displacement ventilation system. Controlled chamber experiments, modeling, and demonstrations are needed to refine integration of the displacement ventilation system for applications in offices, schools, and a variety of other settings.

Filters remove dirt and debris from ventilated air to keep coils, fans, ducts, and internal spaces clean. Because there is a pressure drop across filters, there is a trade-off between filter efficiency and fan size and power. In general, however, filter resistance is a fraction of the total resistance in a ducted HVAC system. Currently, the filters used in office buildings are rated according to ASHRAE Standard 52.1-1992, which involves a dust-spot efficiency test based on discoloration of filter paper upstream and downstream of the filter being rated. An arrestance percentage measures the removal of a synthetic test dust from the air stream by the filter. An arrestance percentage of 90 or 95% may represent only 40% efficiency, as rated in a dust-spot test. Neither procedure indicates how the filter performs when challenged by submicron-sized particles. ASHRAE protocols now under consideration recommend that filters be tested for performance as a function of particle size (e.g., 0.3–10 µm).

Specifying more efficient filters for buildings may not be straightforward, as fan speed and other system adjustments may be required. However, some existing systems may not be retrofitted with higher efficiency filters without substantial cost.

Building Operations

HVAC controls refer to all the electrical and maintenance devices used to monitor and operate a building ventilation system. Controls modulate air inlet, air flow, air temperature, and sometimes humidity to meet specified thermal conditions.

Some control systems are quite complex, consisting of sensors, signal processors, computer or clock controllers, switches, dampers, valves, relays, and motors. Some buildings experience IAQ problems because systems are difficult to inspect, maintain, and operate.

The HVAC system may be operated by direct digital control with a central computer, relying on electronic monitoring. So-called smart systems now in use can continuously track CO₂ concentrations to improve management of the fresh air supply. However, without some form of verification, such as CO₂ levels, many of the current systems are not capable of determining if damper actuators are working as specified.

Most of today's modern office buildings have a sequence of operation for their HVAC systems. Routine events related to building occupancy allow engineers to program HVAC systems. The experience of hearing the HVAC system shut down at 5 PM is quite common. Yet repairs, maintenance and housekeeping activities, and other work may continue many hours into the evening. Particle concentrations, as well as other contaminants, can increase sharply as a cleaning crew enters and vacuums offices after hours, when the HVAC systems are no longer fully operative.

The operating strategies devised for the controlling system have been implicated in building-related IAQ problems. For example, many systems operate on economizer cycles that use the cooling or heating capacity available in the ambient air. During the economizer phase, the outside louvers open. Often there is a temperature range, depending on climate and season, when the outside dampers are completely open. If ambient conditions become too warm and humid, outside air vents return to minimum or closed settings. To protect coils from freezing or to minimize heating, outside air vents also are closed at colder temperatures. Thus internally generated contaminants are subject to varying amounts of diluted air and building occupants may face varying indoor air quality. At times the outside air dampers may be shut fully and 100% of the supply air is made up of return air.

HVAC systems are designed and balanced to meet building ventilation codes and to maintain generally uniform internal pressures. Air leakage of the building envelope leads to infiltration of unconditioned outside air. Further, intentional opening of windows and doors can cause substantial air exchange and pressure imbalances depending on wind, temperature, and structural factors. Even in sealed buildings, plumbing and electrical chases, elevator shafts, and poor construction leave many uncontrolled pathways for pressure-driven internal air flow. Entrainment of auto exhaust, reentrainment of discharged air, and interzone and intrazone movement of air will occur. Depending on the complexity of the ventilation system and the architecture, unmanaged air flows can, at times, be transient and difficult to discern.

Ventilation Requirements

ASHRAE guidelines refer to outside air as the ventilation air and to the supply air as the combination of outside air and recirculated air, but there is still confusion about definitions and terms used in connection with ventilation. Ventilation can be measured in units of air changes per hour (ACH). Total air changes is the number of times the total volume of air in a room is changed each hour with air that includes both recirculated and outdoor air. Hence, it is simply the volume flow rate (liters/sec, cfm) multiplied by time (3,600 sec, 60 min) divided by the physical volume of the room or building. The portion of air recirculated may be local or from elsewhere in the building. The recirculated air is often filtered and reconditioned but not necessarily to any specified efficiency except in special circumstances (e.g., in operating rooms and infection isolation rooms). Further, mixing of the supply air within the zone served by the AHU often is not uniform or complete. Partitions, furniture, office equipment, and plants and books placed on unit ventilators often restrict mixing. Even for a well-mixed space, 1 ACH means that only 63.2% of the original air is actually removed in the first hour. Short-circuiting, obstructions, and thermal gradients can make the mixing efficiency much less than the theoretical limit. However, it can approach 100% replacement per ACH if there is uniform displacement flow without mixing. This strategy is called displacement ventilation and is being used on a limited basis, with research and modeling currently under way in Europe, Japan, Canada, and the United States. It is expected that displacement ventilation rather than recirculation will gain acceptance early in the next century.

Ventilation requirements can be expressed as total and outside air changes.
per hour as they are for hospitals and residences. For example, ASHRAE 62-1989 calls for a minimum 0.35 air exchange per hour rate for residences. The standards for hospital operating rooms are 15 ACH of total air but only 3 ACH of outside air.

Ventilation requirements for office buildings, classrooms, and theaters, among other spaces, are expressed as volume of outside air per person and/or volume flow rates of outdoor air per square foot of building area. Both methods for quantifying ventilation use expected occupancy densities and are supposed to be equivalent. For example, 20 cfm per person—the ASHRAE 62-1989 consensus standard for office space—is based on an estimated maximum occupancy of seven people per 1000 ft². Specifying ventilation based on floor area is useful when planning a generic building. California Title 24 regulations require 0.15 cfm of outside air per ft² of occupied area. ASHRAE standard 62-1989 recognizes the need for a minimum amount of outside air (0.5 cfm/ft²) in low occupancy rooms with pollution sources (e.g., printing and duplicating).

Building ventilation codes also specify the minimum percentage of outdoor air. Minimums may be specified between 10 and 20%, but in practice outdoor air may vary from none to 100%. The amount of outdoor air delivered depends on the design requirements (e.g., air from laboratory fume hoods and kitchen exhaust cannot be recirculated) and the operating specifications. During economizer cycling, dampers open to use the “free cooling” of ambient air. This might happen when the air temperature is between 50 and 65°F. However, to prevent freezing of coils or overuse of air conditioning, dampers may be closed completely.

Critical to the performance of the ventilation system are air distribution and effective mixing. Occupants benefit from the HVAC system when it keeps them in thermal comfort and dilutes odors and contaminants adequately. Thermal comfort ranges for temperature and humidity (latent heat) as well as air velocity and temperature gradients are well defined (9). Occupants, however, experience the conditions by sensing properties of the room (or zone) air at a single point. Individuals might be sensing quite different conditions for several reasons: location of supply ducts and return systems with respect to the individual’s position in the room; barriers and partitions that disrupt air circulation; proximity of sources and the convective pathways of air flow; individual differences in clothing, metabolism, and metabolic rates; and radiative heating and cooling effects of walls, windows, and machines.

Standardized tests for ventilation effectiveness are still under development, but experimental field studies indicate that air mixes well within rooms in commercial office buildings with good mechanical and interior design (10). Nevertheless, short-circuiting and deficient supply to the terminals of some ventilation spaces can cause spatial differences of mixing efficiency across zones within a building. This can happen within a single HVAC zone when open office space is subdivided by high partitions and other obstructions. The net result is inadequate dilution at the individual level, which causes dissatisfaction even when the overall system is thought to perform to the standards.

Implications for ETS Exposure and Control

A number of studies have reported on levels of tobacco smoke particles, nicotine, and other constituents of cigarettes in indoor settings such as offices, restaurants, bars, homes, and transportation conveyances (2). Nonsmokers in these settings are obviously exposed to ETS. Concentrations of ETS components depend on, among other factors, internal mixing, surface-to-volume ratios, and air exchange rate. Exposures to fresh ETS as well as to components that are recirculated and revolatilized will occur in many settings. ETS exposure is dominated by proximity to and the amount of smoking. Mixing of air within a zone will, of course, modify the concentrations and to some extent the constituents. Once ETS is recirculated and mixed with outside air and air coming from nonsmoking areas in the building, concentrations are typically orders of magnitude lower.

Generally, the highest ETS exposures are occurring in bars, taverns, and night clubs, followed by homes and apartments and then offices. Measurements of respirable suspended particles (RSP) by Siegel (11) found restaurants to be 1.6 to 2.0 times higher than in offices and 1.5 times higher than in residences (with at least one smoker). Meisner and colleagues (12) found integrated (hours) levels of RSP in nonsmoking offices in Boston to be less than 30 μg/m³, whereas restaurants and bars ranged up to 140 μg/m³. Collett et al. (13) reported RSP levels averaging between 93 μg/m³ and 151 μg/m³ for neighborhood pubs and nightclubs. Short-term (1–5 min) measurements made by Spengler (14) recorded RSP levels that often exceeded 250 μg/m³ and ranged up to, and sometimes above, 1,000 μg/m³. Lambert and colleagues (15) showed RSP levels that were 40% lower in the non-smoking sections of restaurants but nicotine measurements indicated that ETS exposures occurred throughout the restaurants. Ott and colleagues (16) made repeated visits to a sports tavern to measure RSP before and after a smoking ban. RSP levels decreased by 77%, from 57 μg/m³ to just 13 μg/m³ over outdoor levels.

Predicting ETS concentrations depends primarily on the amount of smoking, air mixing, and movement within the space. For components that exist in two phases (vapor and condensed), such as nicotine, aging of the smoke and surface deposition could present further complications. At the typical ACH of total air (5–7) in office buildings, ETS is rapidly diluted. However, some constituents—again, like nicotine—are re-admitted from the surface after smoking ends. The rate of release is complicated by humidity, temperature, and surface adhesion factors, but measurable concentrations of nicotine have been reported long after smoking has ceased.

Repice et al. (17) conducted Monte Carlo simulation of nicotine exposures in an office setting. Smoker densities and air exchange rates were assessed from ASHRAE standards (ASHRAE 62-1989). An open office space of 1000 ft² with 10-ft ceilings was considered. Ten thousand trials were applied to a physical model in which variation was simulated using assumed standard deviation for the parameters. Results for the distributional concentrations were compared to measured office place integrated nicotine concentrations (18). The Repice model predicted a mean of 8.2 μg/m³ versus 8.6 μg/m³ actually measured and only slightly underpredicted the 90th and 95th percentiles.

Although the data sets for model development and comparisons are limited, it is reasonable for indoor nicotine values to be log normally distributed. However, by today’s conventions, office smoking patterns would depart from the ASHRAE assumption of 29% smokers equally distributed in the work force. Substantially lower workplace exposures can be expected because of recent efforts to segregate smoking. Predicting ETS workplace
exposure for specific individuals is not a fruitful exercise. However, using Monte Carlo simulation techniques and distribution of key variables, researchers can reasonably estimate ETS exposures in workplaces such as offices, restaurants and bars.

**Summary**

Offices are complex microenvironments that are supplied with air by a variety of types of HVAC systems. The HVAC systems are critical for diluting ETS by bringing air into rooms or areas where smoking is taking place. The efficacy of the HVAC system depends on its design and operations. The goal of ASHRAE Standard 62—providing air of quality that satisfies 80% of occupants—seemingly cannot be met for ETS at the current specifications of the standard.

In addition to diluting of ETS, HVAC operations can also move throughout a building air that has been contaminated by ETS. Simple predictions cannot be made about the consequences of these operations because they vary with building and HVAC characteristics. However, an understanding of HVAC systems is needed to develop models to assess exposures of U.S. workers to environmental tobacco smoke.

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