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Design for Smoking Areas: Part 2—Applications

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ABSTRACT

Recent ASHRAE forums have revealed an increased interest in information and guidance relative to designing and applying ventilation systems for areas where smoking is permitted. There are few data currently available through ASHRAE for the engineer challenged with designing a cigar bar, a smoking lounge, or a bar or restaurant with smoking permitted.

This paper applies laboratory data about the acceptance of environmental tobacco smoke to real-world applications. This approach addresses removal effectiveness and ventilation effectiveness associated with airflow patterns that can be established in areas where smoking is allowed. An equation is also presented for calculating ventilation rates for locations where smoking is permitted.

Guidance for the application of the calculated ventilation rates is presented, addressing the location of the smoking area, air distribution device location, use of air-to-air heat exchangers, particle filtration, gas-phase filtration, and use of transfer air. This guidance is based upon literature and data from studies performed in areas where smoking is allowed.

INTRODUCTION

An increased interest in ventilation in smoking areas has been indicated in several recent ASHRAE forums and seminars. This paper is the second in a series of two papers addressing the design of smoking areas. These papers review literature regarding the design of smoking areas, identify gaps in knowledge, and fill in some of those gaps. The goal is to propose methods by which design engineers can apply what is known to smoking area design.

To understand the approach taken in this paper, a number of key points from the first paper (Nelson et al. 1998) should be restated:

- Environmental tobacco smoke (ETS), or second-hand smoke, is a complex mixture of both gas and particulate-phase compounds composed of the aged and diluted combination of both sidestream (smoke from the lighted end of a cigarette) and exhaled mainstream smoke.
- Most of the compounds identified in ETS have other indoor or outdoor sources.
- To determine the contribution from smoking to these compounds in indoor air, one must measure marker compounds.
- The three most commonly used markers for the particulate phase of ETS (ETS-RSP), in order of increasing specificity, are ultraviolet particulate matter (UVPM), fluorescent particulate matter (FPM), and solanesol.
- In the gas phase, nicotine concentrations do not track the concentrations of most other measurable ETS components. The current best marker for the gas phase of ETS is 3-ethenylpyridine (3-EP).
- Experiments performed in controlled laboratory settings suggest that odor is the primary factor associated with sensory evaluation of ETS in the air.
- The specific compounds associated with the odor of ETS are not known.
- Data available in the literature suggest that smokers find air quality acceptable at higher concentrations of ETS than nonsmokers.
- Among nonsmokers in a laboratory setting, 80% acceptability of air quality is achieved when the ETS from one

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cigarette is diluted by 78 m^3 - 120 m^3 (2800 ft^3 - 4200 ft^3) of air.

- ETS concentrations determined in the laboratory are likely to overestimate the impact of ETS on nonsmokers in real-world settings for a number of reasons discussed in this paper.
- Ventilation rates that agree well with those in *ANSI/ASHRAE Standard 62-1989* (ASHRAE 1989) can be derived using demographic averages.

Due to social changes that have occurred in the last decade, today smokers are usually restricted to smaller, more defined areas than they were in the past. For these conditions, which do not fit the average conditions listed in ASHRAE 62-1989, a new design approach is needed. This paper proposes that the results from laboratory studies of the sensory impact of ETS on nonsmokers and the chemistry of ETS can be used to generate a simple model to determine the ventilation rate (as a function of source generation rate and removal rate) needed to achieve 80% acceptability in the field.

DESIGN APPROACH

The design information presented in this paper, combined with the fundamental information presented in the companion paper (Nelson et al. 1998), provide a design engineer with basic assumptions and formulae for designing smoking areas. Following are the design steps and inputs.

1. Estimate the ventilation rate for smoking:
   - How many smokers?
   - What is the smoking rate?
   - How much dilution is required?
2. Determine the design factors that apply:
   - Are the smokers and nonsmokers separated?
   - Does the volume of the space give a large or small time constant?
   - Is a diversity factor for maximum occupancy appropriate?
   - Do airflow patterns maximize removal effectiveness?
3. Determine the minimum outside air required from ASHRAE 62-1989 (minimum Q_{oa}).
4. Design the space and select equipment:
   - Use transfer air when possible.
   - Incorporate air-to-air heat exchangers into the systems to conserve energy.
   - Use filtration as an alternative for supplemental air that is required above the ASHRAE 62-1989 minimum.

Equation for Estimating Ventilation

The design model proposed uses three factors to determine the total volume rate of outside air plus filtered air. These factors are the generation rate, the dilution volume, and the removal effectiveness as they are related in Equation 1:

$$(Q_{oa} + EQ_r) = \frac{GD}{m} \tag{1}$$

where Q_{oa} is the outside air ventilation rate, Q_r is the rate of air recirculated through filters, E is the filter efficiency, G is the generation rate, D is the dilution volume, and m is the removal effectiveness factor. Appendix A contains an example of an application of this equation.

Of these factors, the generation rate represents how many cigarettes or cigars will likely be smoked per unit time. The dilution volume is derived from information discussed in the first paper. The removal effectiveness is a function of the design.

This model is based on four major assumptions.

1. Dilution rates from laboratory studies should be used.
2. The design assumes steady-state conditions.
3. With exceptions noted in the variable occupancy guidance in ASHRAE 62-1989, design should assume maximum occupancy.
4. Since the first three assumptions are conservative, mean values can be used for the other input factors. The three conservative assumptions are assumed to offset the variability or noise introduced by the other input factors.

Derivation

Equation 1 can be formulated from Equation 2 (a model proposed by Ishizu 1980), combined with a simple dilution concentration equation (Equation 3):

$$C_i = C_{r0}e^{-(Q_{oa} + EQ_r)mt/V} + \frac{mC_oQ_{oa} + S}{m(Q_{oa} + EQ_r)}(1 - e^{-(Q_{oa} + EQ_r)mt/V}) \tag{2}$$

$$C_i = \frac{S}{DG} \tag{3}$$

Equation 1 is obtained by combining Equations 2 and 3, assuming steady-state so that the term $e^{-(Q_{oa} + EQ_r)mt/V}$ equals 0; and assuming that the concentration of ETS in the outdoor air C_o equals 0. In the laboratory-validated model by Ishizu, the term m was a mixing factor. In nonlaboratory applications, m will be used as a removal effectiveness factor.

Energy Considerations

Ventilation systems in buildings, except low-rise residential, should comply with *ANSI/ASHRAE Standard 90.1-1989* (ASHRAE 1995b). New guidelines for equipment efficiencies for ventilation equipment, as well as the use of heat recovery devices such as desiccant wheels, heat pipes, or economizers, are under discussion within ASHRAE. Ventilation systems designed for areas with high occupancy densities (such as smoking lounges) can reduce energy consumption if outside air intakes are controlled to a volume below design rates when spaces are partially occupied.

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There are some alternatives to delivering outside air to smoking areas directly through the HVAC system. The first alternative is transfer air. It is essentially free air that can be used from other spaces in a building. For example, the exhaust air from nonsmoking areas in a building can be the supply air to a smoking lounge prior to the air being exhausted from the building.

The second alternative is an air-to-air heat exchanger. Air-to-air heat exchangers can provide desired air quantities without the energy and equipment-sizing penalties of conditioning all outside air in the main HVAC system. They may be either sensible heat devices or total heat devices. Fisher et al. (1983) studied air-to-air energy recovery equipment and determined that for a tobacco smoking application, corrosion is not a concern but that there is some potential for fouling. With a total heat device, cross contamination must be addressed.

INPUT VALUES

In designing smoking areas, values must be obtained for the dilution volume, generation rate, removal effectiveness, and filtration efficiency. These values can be obtained from laboratory studies or field studies. Controlled laboratory conditions are suited to giving values for dilution volumes, mass of combustion compound per cigarette or cigar, and filtration efficiency. Observational field studies are the best source of behavior-related input such as rate of smoking. Field studies can also be used to verify the laboratory behavioral measurements such as acceptance.

The number of field studies that measure ETS concentration, smoking rates, ventilation rates, and occupant responses is limited. Available data from field studies are shown in Table 1. The office in Table 1 is a study reported by Bohanon et al. (1996) where ETS concentration and occupant responses were measured in an office building that was operated at three different ventilation rates. The lounge is that reported by Straub et al. (1993).

Bohanon and Curl (1994) reported on a pub and a barbecue restaurant (restaurant B in Table 1). Restaurant C is a bar and seafood restaurant located in a mid-Atlantic suburban area. Restaurant D is a bar and Mexican restaurant located in a western city. The data collected included ETS concentrations, smoking rates, and a ventilation assessment.

The authors of this paper recently measured conditions in five restaurants located in the southern U.S. Restaurant 1 was a diner style restaurant that did not have a separate nonsmoking section. All other restaurants tested had separate sections. Restaurant 2 was a steak house, restaurant 3 was located in a hotel, restaurant 4 was a seafood restaurant, and restaurant 5 was an upscale grille. The data collected included ETS concentrations, smoking rates, ventilation assessment, and patron responses.

Dilution Volume

The dilution volume for nonsmokers is different from that for smokers. Nonsmoker data were obtained from two laboratory studies. A recent study by Walker et al. (1997) is in general agreement with Cain et al. (1983) who concluded that a dilution of 78 m^3 - 120 m^3 (2754 ft^3 - 4237 ft^3) per cigarette would place acceptability at about 75% to 80%. For smokers, data from the studies of Straub et al. (1993), Cain et. al (1983), and Leaderer et al. (1984) suggest that a volume of 25 m^3 - 40 m^3 (883 ft^3- 1412 ft^3) per cigarette would ensure a minimum of 80% acceptance. See the companion paper (Nelson et al. 1998) for further discussion of these studies.

The authors know of no studies that have measured acceptability from cigar smoking. Therefore, the engineer must make assumptions. The available data indicate that a cigar may produce four times the particulate matter of one cigarette and 10 times the TVOC of one cigarette (Nelson et al. 1997). It would be logical to assume that ETS from one cigar is equivalent to ETS from four to ten cigarettes.

Generation Rate

The smoke generation rate (G) can be estimated by observing smoking behavior in an existing location. This direct estimate is made by counting cigarettes actually smoked during a period of time. When a direct observation is not possible (for a brand new location), the generation rate must be determined by other means. In Equation 4, the generation rate is broken down into three factors: the occupancy or number of people (P), the fraction of smokers (f_s); and the rate of smoking per smoker (R).

$$G = Pf_sR \qquad (4)$$

Occupancy. An assumption frequently made in ventilation design is that occupancy is constant. In some cases, that may be a good assumption, but for many bars and restaurants the occupancy is highly variable.

The area of the pub studied by Bohanon and Curl (1994) is 300 m^2 (3000 ft^2). The estimated maximum occupancy factor from Standard 62-1989 is 70 people per 100 m^2 (1000 ft^2), resulting in an estimated maximum occupancy of 210 people. The actual occupancy was measured every 30 minutes during two weeks of testing. Figure 1 shows the pattern through the day, illustrating that occupancy in the real world can differ significantly from a constant value. For design values, follow the guidance of Standard 62-1989 for variable occupancy.

Fraction Smokers. In the laboratory, the ETS generation rate can be held constant. In the real world, the generation is a function of the number of smokers present and their smoking rate. In the pub, the people in the smoking section and the nonsmoking sections were counted. It is likely that some nonsmokers joined friends who are smokers in the smoking section and vice versa. In some field tests, the count of actual cigarettes smoked can only be related to the number of people (smokers and nonsmokers) observed in the smoking section.

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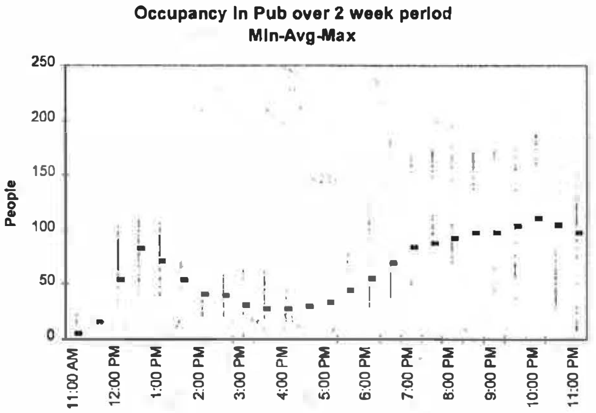

Figure 1 *Time distribution of occupancy in the pub.*

Smoking Rates. Table 1 gives observed smoking rates from several studies. The overall percentage of occupants in the smoking section (or percent smokers in two cases) is shown for various types of facilities. The rate of smoking for the people in the smoking areas is also shown.

Figure 2 shows the cigarettes smoked per hour per person as a function of the number of persons seated in the smoking area of the pub. This figure illustrates that a single observation is unlikely to be representative of occupant behavior. In retrofit or modification applications, several observations are required to accurately determine smoking rates.

Removal Effectiveness

One necessary, simplifying assumption of single-compartment modeling is that the air is well mixed. This condition is usually achieved in laboratory settings by the use of circulating or mixing fans.

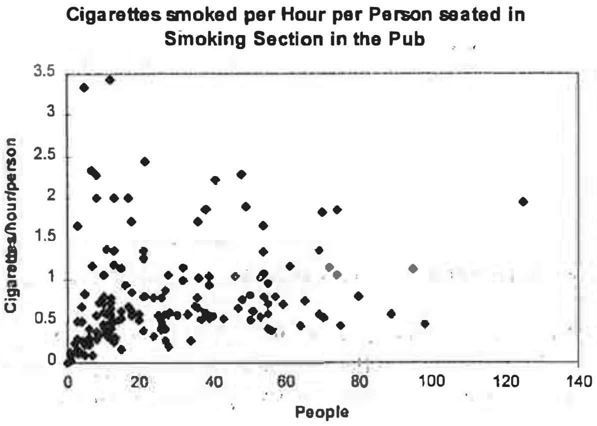

Figure 2 *Smoking rate for persons seated in the smoking section vs. occupancy.*

In the perfectly mixed condition, the air is homogeneous. The air is of the same age in all parts of the room where the age is the time that has transpired since the parcel of air entered the space from the outside. In these mixed conditions, the ventilation effectiveness is equal to one. Ventilation effectiveness is calculated from Equation 5:

$$\varepsilon_{l,L} = \frac{\tau_N}{\Theta_{age,L}}. \qquad (5)$$

This is the same as Equation 22 in *ASHRAE Fundamentals* (1997, chapter 25). The local ventilation effectiveness $\varepsilon_{l,L}$

TABLE 1
Observations from Past Tests

Date	Location	Hours Observed	Occupants Average/ Maximum	% Smokers	Cigarettes /h/ Smoker
1992	Office	88	124 / ND	32%	1.3
1990	Lounge	N/A	14 / 14	100%	3.3
1992	Pub	168	62 / 210	58%*	0.57
1992	Rest B	148	51 / 144	53%*	0.69
1992	Rest C	114	23 / 118	42%*	1.28
1992	Rest D	100	40 / 47	58%*	0.71
1996	Rest 1	8	23 / 38	100%*	0.61
1996	Rest 2	8	18 / 44	52%*	0.96
1996	Rest 3	8	24 / 49	45%*	0.45
1996	Rest 4	8	26 / 45	38%*	0.75
1996	Rest 5	8	51 / 90	26%*	0.82

* Denotes that percent smokers is percent of occupants located in smoking section

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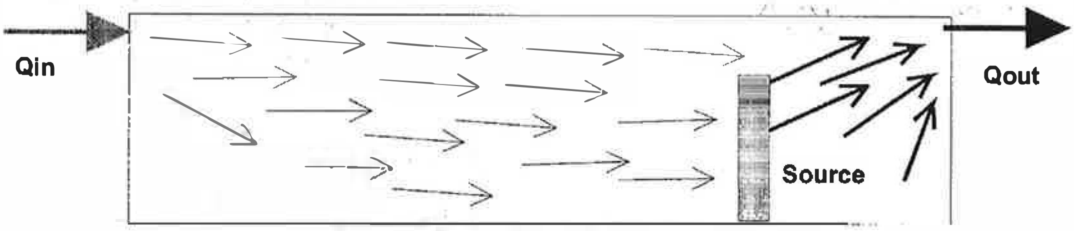

Figure 3 *Diagram of a room with one source and plug flow.*

is the nominal time constant τ_N divided by the age of the local air $\Theta_{age,L}$. Ventilation effectiveness focuses on good distribution of the outdoor air and how long it has been in the space.

A similar concept is removal effectiveness. Because this design focuses on removing ETS, removal effectiveness should be emphasized. Removal effectiveness measures the removal of the contaminant in the space or how long the contaminant remains in the space. Removal effectiveness is a function of airflow in the space.

Airflow patterns have an important effect on acceptability in a local environment. The effect of special air distribution configurations on environmental tobacco smoke concentrations have been reported in the literature (Faulkner et al. 1993; Akimoto et al. 1995; Burnley 1993). Straub et al. (1993) tested the acceptability of different configurations of standard air-distribution and displacement systems in a smoking lounge. With the ventilation rate controlled to a constant 60 cfm per person in the smoking lounge, the acceptability ranged from 45% to 93% as the local air-distribution method varied.

Plug flow is described as unidirectional airflow ventilation by ASHRAE (1997). Displacement ventilation is a related concept where, in common with plug flow, mixing is minimized by design.

For the example of a long room (Figure 3), the source is located at a distance three-fourths of the length of the space with perfect plug flow (no mixing). In this space, the source is localized near the exhaust. If one assumes that the source and its emissions occupy one-fourth of the space and that this space is in the exhaust stream, then the average age of the emissions is one-fourth that of the room air. For a room under these conditions, the removal effectiveness would be 4. The average concentration in the room is one-fourth of the well-mixed case. The proper interpretation of these conditions is that three-fourths of the room has no concentration of the emission and one-fourth has a full concentration.

In a situation where the flow is only partial plug flow and some of the air is recirculated, the partial plug flow can have a significant effect on the concentration observed in the space. In the case of the pub (Bohanon and Curl 1994), the air flowed toward the kitchen and the exhaust fan. The pub had three rooms that were connected by open doorways and the HVAC system had a common return. The layout of the pub is illus-

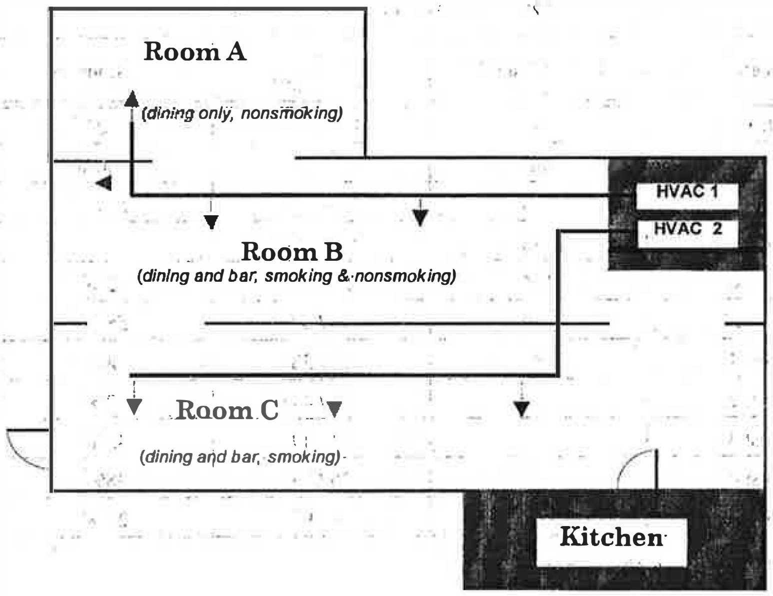

Figure 4 *Diagram of pub before HVAC modification.*

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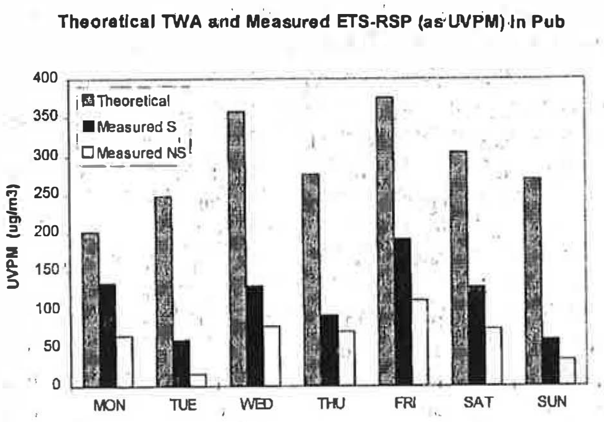

Figure 5 *Theoretical average particle concentration vs. measured concentrations in the pub before changes to the ventilation system.*

trated in Figure 4. The pub had no outside air supply and all ventilation was infiltration induced by the kitchen exhaust fan.

Figure 5 shows the actual measured concentrations in the smoking (S) and nonsmoking (NS) sections, along with the theoretical value if the pub was a well-mixed laboratory chamber. The differences in theoretical and actual concentrations are likely a result of a partial plug flow in the pub. The filter on the HVAC system before modification was not efficient for particles in the ETS-RSP size range; however, some particle deposition may have occurred.

In a controlled experiment, Curl et al. (1995) tested the effect of ventilation and separation on ETS concentration in an office space. The smoking rate was controlled and the space was configured with the smokers near the return/exhaust when they were separated from the nonsmokers. This configuration was equivalent to a restaurant with the smoking section near the return/exhaust. In the Curl et al. (1995) study, the ventilation rate was controlled and varied from a totally sealed HVAC outside air intake to full economizer mode.

Bohanon and Cole (1997) evaluated several published models for predicting ETS-RSP concentration using the data set obtained in the Curl et al. (1995) study. The models were developed from fundamental theory or from laboratory data. The predictions are listed in Table 2. The models greatly overpredict ETS concentration. The models and the test accounted for filtration, time, and generation rate. The biggest difference between these models and the test conditions is that the test space was not well mixed. The plug flow resulted in a removal effectiveness that was not accounted for in the models.

Filtration Efficiency

Essentially, ventilation reduces the concentration of indoor air contaminants by dilution. Recirculation of filtered air back to a space may also be used to reduce contaminant concentrations by dilution. Equation 1 contains two terms related to the use of air filtration to supplement outdoor air for the reduction of ETS concentrations: E, the filtration efficiency, and Q_r, the amount of air that passes through an air filter. In practice, the amount of dilution air provided by filtration is a product of the efficiency of the air filter and the airflow through the media. For example, an air filter operating at 1700 m^3/h (1000 cfm), which removes 50% of the ETS particles that pass through it, delivers an equivalent 850 m^3/h (500 cfm) of particle-free air to a space.

As is the case with heat exchangers, filtration carries with it the additional advantage that the dilution air is supplied without the energy costs associated with conditioning outdoor air. However, in contrast to the straightforward application of air-to-air heat exchangers, use of air filtration to control ETS is more complex. When dealing with the filtration of ETS, it is important to separately consider gas and particulate filtration. Removal of particles is relatively straightforward, but additional considerations must be made when selecting filtration media for the gas phase of ETS. In this section, each type of filtration media and its application to ETS will be summarized.

Both gas and particulate filtration can be effectively applied to the removal of ETS from indoor air. Depending on the design goal, the application of air filtration to indoor air may reduce the need for supplying conditioned outside air above ASHRAE-specified minimums to spaces in which smoking takes place. Additional general information describing gas and particulate filtration is available from a number of sources (NAFA 1993; ASHRAE 1995a, 1996).

Particles. ETS can be a significant source of particles in indoor air. Although the mass of particles generated by smoking is small relative to the total mass of gases produced (Martin et al. 1997), the removal of ETS particulate matter is desirable from several standpoints. Removal of the particulate matter may lead to reduced deposition of particles on interior surfaces with a concurrent reduction in the staining of materials. The particles are also responsible for the visible smoke in the air. When they are removed, any smoke haze in the air will be reduced. In addition, removal of ETS particles may help to decrease the amount of tobacco smoke odor in a space. Low volatility compounds in the smoke particles may off-gas,

TABLE 2
Measured and Model-Predicted ETS-RSP ($\mu g/m^3$) from Bohanon and Cole (1997)

Model Ventilation	Actual	Mod1	Mod 2	Mod 3	Mod 4	Mod 5	Mod 6	Mod 7	Mod 8
Max. OA (7.8 ACH)	3	111	36	35	108	177	168	33	35
Min. OA (0.4 ACH)	22	1045	314	252	836	2571	1143	731	464

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and be responsible for at least some of the detectable smoke odor in a space. Removal of the particles in a well-maintained system has the potential to reduce the odors associated with smoking.

There are a number of methods for evaluating the performance of particulate air filters (ASHRAE 1996). For corded electric air cleaners, a trade association of home appliance manufacturers has developed a standard based upon the equivalent volume of clean air produced by the air cleaner (AHAM 1986). Using their standard, effectiveness is reported as clean air delivery rate (CADR). The CADR is directly equivalent to the term EQ_r found in Equation 1. Among high-efficiency filters, such as HEPA and 95% DOP, the efficiency (E) is essentially equivalent to 1. For other filters, it is important to ascertain the effectiveness for ETS-sized particles for reasons described below.

Environmental tobacco smoke particles are quite small. Their mass median diameter is typically reported to be in the range of 0.1 µm - 0.5 µm (Guerin et al. 1992), and they may not be removed from the air by typical HVAC filters. Physical filtration relies on impaction on, and diffusion to, fiber surfaces to remove ETS particles from the air. The size of ETS particles is such that both removal mechanisms are relatively inefficient.

To remove ETS-sized particles, high-efficiency filters such as HEPA and 95% DOP rated filters are typically employed. The cost and impact on air-handling system design (fan sizing and power) may make these filters impractical for whole buildings. But physical filtration can be effective when employed in air cleaners designed for cleaning room-sized spaces (Jaisinghani et al. 1989; Pierce et al. 1996).

In many cases, electrostatic precipitation (EP) is a near ideal solution for ETS particle removal. EP units require relatively little energy to operate and provide an extremely low pressure drop when installed in either whole-building systems or individual air cleaners. One concern commonly cited when electrostatic precipitators are operated is their potential to generate ozone. Problems with ozone generation can be overcome in a properly designed EP unit or can be ameliorated by the use of post-filtration media designed to remove ozone.

Regardless of the media chosen for the removal of particulate matter, proper maintenance of particulate filtration media is of paramount concern. Media-based filters will effectively remove ETS-sized particles for a long time before becoming saturated; however, there is potential for off-gassing of low-volatility odorous materials from the media. In addition, there may be other sources of particles in the air that may load the face of the media, resulting in either decreased effectiveness (E remains high but Q_r decreases) or increased utility costs associated with moving air through the media as the pressure drop increases. The efficiency of electrostatic precipitators will decrease if the collection plates are allowed to build up a nonconductive layer of material on their surface. Regular cleaning (a relatively simple washing process) at manufacturer-specified intervals is critical for maintaining optimal effectiveness of electrostatic precipitators.

Gas Phase. Gas filtration can provide a useful and important adjunct to the particulate filtration of ETS. A wide range of media are available, or in development, for the removal of gaseous contaminants from indoor air. They generally can be divided into two general classes. One class of media is adsorbents. Adsorbents are characterized by a large surface area onto which gaseous contaminants may be physically or chemically adsorbed. The other class of media is chemically reactive. Two examples of media that are in this category are permanganate-based media and catalytic media. Permanganate chemically reacts with some types of indoor air pollutants. Catalysts facilitate the reaction of contaminants with air; however, unlike permanganate, they are not consumed in the reaction process.

In contrast to the particulate filters, there are no standard methods for determining the effectiveness of gas-phase air filters. There are a number of challenges facing the development of standard testing protocols for gas-phase air filtration media. One challenge is a result of the wide range of chemical properties of gas-phase indoor air contaminants. For example, formaldehyde is difficult to remove from the air using activated carbon, but it is effectively removed by reactive media, such as permanganate-impregnated alumina or silica. On the other hand, the reactive media are less effective than activated carbon at removing typically encountered volatile organic compounds (VOCs). In developing test methodologies and evaluating media performance, it is important to realize that removal effectiveness of filtration media is not uniform across all chemical compound classes found in indoor air (Nelson et al. 1993a).

To maximize success with gas-phase filtration, it is important to have some idea of the classes of compounds to be removed and to tailor the selection of filtration media to maximize removal of those compounds. For complex mixtures such as ETS, a variety of filtration media (adsorptive and reactive) may be necessary to obtain optimum removal of ETS components.

Another challenge facing development of standard testing methodologies is the wide-range configuration of gas-phase filtration systems. Systems designed for use in large systems range from media trays or beds to specially impregnated fibrous media. Likewise, air filtration units come in a wide range of configurations and capacities. Development of a one-size-fits-all solution is difficult to accomplish.

As a result of these challenges, no standard methods currently exist for determining the effectiveness factor (E) for gas-phase filtration equipment. ASHRAE is currently attempting to develop such standards, but they may not be ready for several years. A number of methods for evaluating gas-phase filtration media have been independently developed. For example, a method of determining effectiveness and lifetime of gas-phase filtration media for indoor air has been developed by VanOsdell et al. (1996). Separately, a method for

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determining CADR for gas-phase components has been developed and applied to air cleaners (Nelson et al. 1993b, 1996). Both methods show promise for comparative evaluation of air filters and media, but neither has been validated in an interlaboratory evaluation.

Commonly used adsorbent media include activated carbons, zeolites, and alumina, but others may also be found in the literature and practice. The adsorbents are typically supplied in pellet or flake form. Additionally, small adsorbent particles may be incorporated into fibrous media or a foam matrix. Within each piece of adsorbent media is a microscopic network of pores into which contaminant molecules may diffuse and adsorb. The presence of a large number of microscopic pores gives rise to a large surface are per unit weight of adsorbent media. The affinity of the media for a particular contaminant is a function of chemical properties of the media, pore size, and number of pores. In some cases, adsorbent media can be modified to increase its affinity for particular classes of compounds. For example, impregnation of activated carbon with phosphoric acid increases its capture and retention of gas-phase bases.

Gas-phase filtration media will eventually become saturated with contaminants. The time to reach saturation varies as a function of that contaminant. As media becomes saturated by a contaminant, a number of events can take place. A fraction of the contaminant will pass uncaptured through the media. In addition, the contaminant may be displaced from the media by another contaminant. In that case, the previously captured contaminant will be re-released into the air supply. For these reasons it is important to (a) choose a media that is well suited to the gases to be removed and (b) routinely maintain a system containing adsorbent media, including replacement of the media at manufacturer recommended intervals.

Other Devices. Devices using technologies other than filtration have been marketed by some for cleaning tobacco smoke from the air. The filtration efficiency (*E*) is not available for these devices.

The use of ozone is often touted as a panacea for the removal of gas-phase contaminants from indoor air. However, considerable controversy surrounds its use in indoor air. Ozone is a criteria pollutant and its maximum allowable concentration (8 h TWA) is regulated in both indoor (OSHA 1994) and outdoor air (EPA 1997). Some ozone generators are capable of producing hazardous levels of ozone within a short period of time (Shaughnessy and Oatman 1991). Furthermore, the efficacy of ozone, at low concentrations, for the removal of gaseous pollutants has not been documented in the literature (Boeninger 1995). Human sensory results (unpublished) obtained in conjunction with the study by Nelson et al. (1993b) showed that the use of an ozone/negative ion generator (a) produced unacceptable ozone levels at the manufacturer's recommended settings and, (b) when adjusted to produce acceptable ozone levels, produced more odor and eye irritation (over time) than ETS alone. Other work by Nelson (unpublished) has shown the rapid oxidation of NO to NO_2 by ozone and only a minor decrease in nicotine concentrations when ozone is used to clean the air. In light of the potential for generating hazardous ozone levels in indoor environments and a lack of scientific data supporting its efficacy, the use of ozone alone for treating ETS in indoor air is not recommended.

Ions can be generated by certain devices. In theory, they charge particles and cause the charged particles to attach to surfaces. Ionization can take place within electrostatic precipitators or it can be externally induced in a variety of air filtration products. There is little, if any, documentation of their effectiveness in the scientific literature. Ion generators are likely to assist in the removal of ETS particulate matter, but it is likely that effectiveness will vary from one product to the next.

Ultraviolet radiation can provide the energy needed for the decomposition of some types of organic compounds. One accepted use of ultraviolet radiation is the killing of airborne microorganisms in the air. However, the efficacy of using ultraviolet radiation for removing ETS or ETS-related compounds has not been demonstrated.

ASSUMPTIONS

Having discussed how to determine the input values for Equation 1, four inherent assumptions in this equation should be examined. The nature of the assumptions determines the applicability of an equation, or model, to a situation. The assumptions are discussed in the following sections in order to help the designer understand the bounds and limits for use of this equation.

Dilution Volume

Dilution volume is inversely proportional to concentration and is the design parameter specified to control the concentration of ETS to a certain level. Despite the fact that evidence strongly suggests that people in the field respond less intensely than those in the laboratory to similar ETS concentrations, it is assumed in Equation 1 that in extrapolating from the laboratory to the field, people will respond in a similar fashion when exposed to a similar concentration of ETS in both settings. The conservative nature of this assumption can be seen by examining four sets of data (two from laboratories, one from offices, and one from restaurants). The two laboratory data sets where ETS-RSP concentration and percent acceptance were measured are the studies of Cain and colleagues (Cain et al. 1983; Leaderer and Cain 1993; Leaderer et al. 1984) and the studies of Walker et al. (1997). The office data are from Bohanon et al. (1996). The restaurant data were measured by the authors. Table 3 shows a summary of the number of responses from the laboratory and field tests.

Figure 6 shows that for ETS-RSP concentrations relative to the real world, the laboratory responses are much less acceptable than the responses measured in the field.

The increases in acceptability found in the field vs. the laboratory may be due to a number of factors that can affect

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TABLE 3
Number of Persons Responding in Each Study

Data Set	n	Responses from Each Subject	Total Responses
Cain Visitor (Moderate RH)	92 Total Subjects 25 Each Condition	NA	275
Walker Nonsmoker	17 Total Subjects 17 Each Condition	14 for Each Condition	238
Bohanon Offices	135 Total Subjects 91 Avg. Daily Responses	11 Days Testing	1003
Five Restaurants	370 Patrons	1	370

occupants' perception. For example, architectural features such as walls or screens can impact the perception of ETS. Moschandreas et al. (1992) found that visual stimuli can affect reported odor strength. In that study, subjects were asked to rate odor intensity under conditions where they were and were not able to see a person smoking. The subjects reported that the same controlled odor was stronger when they were able to see a person smoking.

Steady State. The steady-state assumption tends to overestimate the ETS concentration most of the time. In evaluating the steady-state assumption, compare the laboratory chamber used by Walker et al. (1997) to the pub studied by Bohanon and Curl (1994).

The volume of the laboratory chamber is 45 m^3 (1600 ft^3). The ventilation was controlled between 28 and 180 m^3/h (17 - 106 cfm) in the lab. The volume of the pub is approximately 1000 m^3 (35000 ft^3). The ventilation was estimated to be 1170 m^3/h (690 cfm) in the pub.

One way to compare these spaces is by using the time constant. The nominal time constant τ_N is the time required for one air change if ideal plug flow (no mixing) existed. The nominal time constant is the inverse of air exchange rate I (ASHRAE 1997).

$$\tau_N = \frac{V}{Q_{oa}} \tag{6}$$

$$I = \frac{Q_{oa}}{V} \tag{7}$$

Assuming that ETS particles are generated by smoking at a constant rate and that the other assumptions associated with the simple model hold, Figure 7 shows the predicted concentration as a percentage of each respective steady-state value vs. time. Under the assumed conditions, the steady-state value is the maximum value attained in a space. Estimates based on steady state will overestimate concentrations until the concentration approaches the steady-state value. There is clearly a difference between the lab and the pub. The steady-state assumption is fairly good for the lab over a one-hour period, but this assumption overestimates concentrations for the pub because the time constant in the pub is relatively long.

Occupancy

The directions in Standard 62-1989 for determining occupancy for spaces with intermittent or variable occupancy are valuable because in almost all cases they tend to overestimate occupancy.

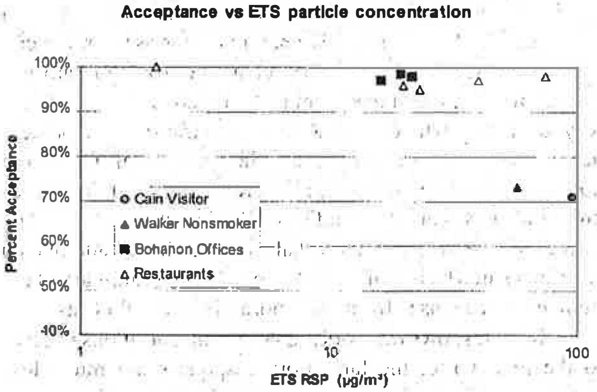

Figure 6 Acceptance as a function of average ETS-RSP concentration.

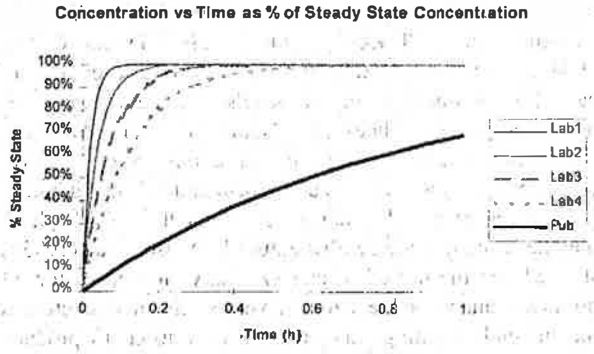

Figure 7 Theoretical concentration of ETS particles for lab and pub expressed as percent of steady state.

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TABLE 4
Ventilation Rate in m^3/h·Person (cfm/Person) for Observed Occupancies*

Date	Location	Measured % Dissatisfied	Average Occupancy	Peak Occupancy	ASHRAE 62-1989	$(Q_{oa} + EQ_r)$ Equation 1
1992	Office	2%	13 (7.6)	13 (7.6)	34 (20)	41 (24)
1992	Office	1%	25 (14)	25 (14)	34 (20)	41 (24)
1992	Office	3%	60 (35)	60 (35)	34 (20)	41 (24)
1996	Rest. 1	2%	46 (27)	28 (16)	34 (20)	70 (41)
1996	Rest 2	0%	110 (64)	46 (27)	34 (20)	56 (33)
1996	Rest 3	4%	ND	ND	34 (20)	24 (14)
1996	Rest 4	5%	71 (42)	41 (24)	34 (20)	33 (19)
1996	Rest 5	3%	26 (15)	14 (8)	34 (20)	24 (14)

* $D = 120$ m^3 (4237 ft^3) dilution volume, and m=1 in Equation 1. ND = not determined.

> Where peak occupancies of less than 3 hours occur, the outdoor airflow rate may be determined on the basis of average occupancy for buildings for the duration of operation of the system, provided the average occupancy is not less than one-half the maximum (ASHRAE 1989).

For the occupancy of the pub (Figure 1), the evening occupancy is longer than three hours. Therefore, using the average occupancy of 62 people is inappropriate. Using a three-hour moving average to determine the peak three-hour period observed results in 180 people, which is very close to the estimated maximum of 210. Using the observed or estimated value for occupancy is appropriate, but as illustrated in Figure 1, the average occupancy will be much lower, assuming the peak occupancy overestimates for all other times.

Use Mean Values for Other Factors

The overestimates of ETS concentration produced by the three conservative assumptions used (laboratory-determined dilution volume, steady state, and peak occupancy) more than compensate for the variability that will be seen in the other input variables. Ventilation rates are calculated from Equation 1 using these conservative assumptions and mean values for other input values. Table 4 lists the measured percent dissatisfied, the measured ventilation rate for design and average occupancy, the minimum rate from Standard 62-1989, and the calculated $(Q_{oa} + EQ_r)$. In calculating the values of $(Q_{oa} + EQ_r)$, the removal effectiveness factor (m) is assumed to equal 1. In almost every case, the calculated value for $(Q_{oa} + EQ_r)$ exceeds the measured value and in every case the acceptability (percent dissatisfied subtracted from 100%) exceeds 80%, indicating that the overall output of Equation 1 for these cases gives a conservative value.

SUMMARY

An equation is presented for calculating ventilation rates for smoking areas. Determination of the values for key inputs is discussed. The inputs are dilution volume, generation rate, removal effectiveness, and filtration efficiency.

In a system design, it is desirable to choose a ventilation rate that will keep ETS concentrations below the targeted concentration at most times. This is accomplished by assuming maximum, rather than mean, values for some of the input variables. The upper bound, or maximum, factors are used for three of the factors in the governing equations (dilution volume, steady state, and occupancy). Available field data indicate that using these assumptions will result in conservative design values.

The information provided in this and the companion paper are a starting point for the engineer designing a smoking area. Understanding principles from ASHRAE handbooks, standards, and especially the literature on air distribution is also prerequisite to the successful design of smoking areas.

ACKNOWLEDGMENTS

We would like to acknowledge the work of David Taylor and David Heavner in the 1996 field study of the five restaurants.

NOMENCLATURE

C_i = concentration of substance in room (µg/m^3)
C_o = concentration of substance in outdoor air (µg/m^3)
C_{r0} = concentration of substance in room at time 0 (µg/m^3)
D = dilution volume (m^3/cigarette)
E = filtration efficiency (dimensionless)
fs = fraction smoker (smokers/occupants)
G = generation rate (cigarette /h)
I = air exchange rate (h^{-1})
m = removal effectiveness (dimensionless)
P = number of people (occupants)
Q_{oa} = outside air ventilation rate (m^3/h)
Q_r = volumetric rate of air recirculated through the filter (m^3/h)
R = smoking rate (cigarettes/h-smoker)
S = generation rate (µg/h)

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t = time (h)

V = volume (m^3)

$\varepsilon_{I,L}$ = local ventilation effectiveness (dimensionless)

τ_N = nominal time constant for air exchange in the space (h)

$\Theta_{age,L}$ = local age of air (h)

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APPENDIX A
EXAMPLE CALCULATION

As an example of how to apply these principles, consider the case of a restaurateur who presents the following design requirements. The small restaurant is 6 m by 9 m (20 ft by 30 ft), seats 40 people, and has one four-top table for cigar smokers who are expected to smoke one cigar each during a two-hour sitting. The two sittings will be fully occupied most of the time and the nonsmokers should find the air acceptable.

Use Equation 1 and Equation 4.

$$(Q_{oa} + EQ_r) = \frac{GD}{m} \qquad (1)$$

$$G = Pf_sR \qquad (4)$$

The input values can be determined from this information. The value of P is 40 with no reduction for diversity since the three-hour occupancy will often be 100%. The minimum outside air (Q_{oa}) from ASHRAE 62-1989 is 1360 m^3/h (800 cfm). The dilution value for cigars can be estimated from the companion paper (Nelson et al. 1998) based on the observation that the average TVOC emission from cigars is 10 times that for cigarettes. So the dilution factor, D, equals 1200 m^3/cigar (42000 ft^3/cigar). The values $fs = 0.1$ and $R = 0.5$ are given. Assuming that $m = 1$, the value calculated for ($Q_{oa} + EQ_r$) is 2400 m^3/h (1333 cfm).

Assume that a separate calculation reveals that the air-conditioning system fan delivers 1700 m^3/h (1000 cfm). How can you get from the delivered rate from the air-conditioning system to the required rate based on Equation 1?

One approach is to specify the air-conditioning system to deliver 100% outside air and incorporate an air-to-air heat exchanger into the system. In order to establish a plug type flow, require that the smoking table be located in the back corner and locate the return to the air-to-air heat exchanger exhaust above the corner table reserved for the cigar smokers. Locate all supply diffusers in the nonsmoking area. Recommend extra separation distance around the cigar table. Equation 1 suggests that this system will work if $m = 1.3$ (removal effectiveness factor). Knowledge of room air movement suggests that the average linear air velocity at the end of the room will be 1.5 m/min (5 fpm), and in the corner the area will be higher, so the removal effectiveness factor of 1.3 does not seem unreasonable. If, as in this example, the removal effectiveness is a part of the design, the restaurateur should be advised to avoid installing ceiling fans or other devices that could counteract the established plug flow.