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Design for Smoking Areas: Part 1—Fundamentals

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ABSTRACT

ASHRAE currently provides little practical information for optimizing the design of a cigar or smoking lounge, although recent ASHRAE forums have indicated an increased interest in this area. This paper provides a summary of the measurement of environmental tobacco smoke (ETS) from cigarettes or cigars, the manner in which ETS concentration varies with rates of smoking and ventilation, and the relationship between ETS concentration and indoor air quality.

During the past two decades, a large number of studies have been published on the chemistry of ETS and how it changes over time, under either controlled laboratory or more real-world conditions. Controlled laboratory exposure studies have been used to predict occupant and visitor responses to ETS in indoor environments. Based on the information from chamber studies, field studies, and engineering experience, a method is proposed for determining the ventilation required to maintain air quality in different situations where smoking occurs.

INTRODUCTION

In recent ASHRAE seminars and forums, an increased interest in ventilation in smoking areas has been indicated. Some ASHRAE publications on this topic include those of Yaglou (1955), Thayer (1982), and Leaderer and Cain (1983). More recently, additional information and new technologies have become available to the design engineer.

This paper is the first of two addressing the design of smoking areas. Their purpose is to review literature regarding the design of smoking areas, identify gaps in knowledge, and fill some of those gaps. The goal of these papers is to propose methods by which design engineers can apply what is known to smoking area design.

This paper addresses current information on environmental tobacco smoke (ETS) and provides guidance for determining the ventilation required to maintain acceptability in a smoking space. The companion paper provides a method for calculating ventilation air requirements for areas in which smoking takes place and provides information on adjuncts to ventilation for maintaining air quality. Information on the chemical and physical properties of ETS provides a framework for evaluating both ventilation design and the sensory impact of ETS on occupants of, or visitors to, a space in which smoking is permitted. A review of available data relating sensory responses to ETS concentrations in controlled settings provides the foundation for determining ventilation rates necessary to achieve acceptable indoor air quality. Basic sensory results and knowledge of the chemical composition of ETS provide input for a simple model for predicting required ventilation rates for smoking environments. In the companion paper, a model for predicting ventilation air needed for smoking spaces is proposed, practical tools, such as filtration and heat exchange, for maintaining good ventilation in a cost-effective manner are presented, and additional factors affecting extrapolation from the laboratory to the real world are discussed.

CHARACTERISTICS OF ETS

Environmental tobacco smoke, or ETS, is the aged and diluted combination of both sidestream smoke (SS), smoke from the lighted end of a cigarette, and exhaled mainstream smoke, smoke that is exhaled by a smoker (Rodgman 1992), a definition that can logically be extended to include the generation of smoke from other articles such as pipes or cigars. ETS consists of materials in both the gas and particulate phase. Both phases are usually considered separately when ETS is characterized. The term "second-hand smoke" is often used in the lay press as a synonym for ETS.

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It is important to note that ETS is an aged aerosol. Many compounds found in mainstream and sidestream smoke particles volatilize rapidly. One example is nicotine. Nicotine is primarily found in the particulate phase of mainstream smoke, but in ETS, greater than 90% of the nicotine is found in the vapor phase (Eudy et al. 1986; Eatough et al. 1986; Ogden et al. 1993). As ETS ages, reactive compounds in either the gas or particulate phase may react or undergo photolysis.

The difference in composition of mainstream and sidestream smoke may also lead to difficulties when aged and diluted sidestream smoke is used as a surrogate for ETS (Smith et al. 1992). When a cigarette is left to burn in an ashtray or smoked using a machine, little or no mainstream smoke is generated and a greater proportion of tobacco is burned to form sidestream smoke than when cigarettes are consumed by a smoker. Compounds that are present in different proportions in sidestream and mainstream smoke will have their relative concentrations skewed when only sidestream smoke is generated (Nelson et al. 1998).

Approximately 100-200 compounds have been quantified in ETS (Guerin et al. 1992). The complexity of mainstream and sidestream smoke suggests that a greater number of compounds are actually present, but the vast dilution of ETS makes it impossible to accurately detect or quantify the vast majority of compounds that have been observed in other smoke streams.

Particles

ETS particles are generally thought to consist of small semi-liquid droplets. Materials that make up the particles can originate directly from the tobacco leaf or from partial combustion and pyrolysis of organic material within the leaf. Estimates of the ETS particles' size distribution vary depending on the type of instrumentation used to characterize the particles; the ETS particle size range falls at the extremes of the two most commonly used measurement techniques. Based on measurements of diluted SS, the mean diameter of ETS particles is 0.098 µm with a mass median diameter of 0.185 µm. At high particle concentrations (>220 µg/m^3), that size distribution shifts to a mean diameter of 0.141 µm with a mass median diameter of 0.21 µm (Nystrom and Green 1986). All of the particles in ETS are of respirable size; consequently, they are often referred to as ETS-respirable suspended particles (ETS-RSP).

Chemical characterization of ETS particles is less complete than gas-phase species. A list of compounds expected to reside at least partially in the particles would include polycyclic aromatic hydrocarbons (PAHs), solanesol, +α-tocopherol (vitamin E), scopoletin, and phenols (Benner et al. 1989; Guerin et al. 1992; Ogden and Maiolo 1992; Risner and Cash 1990; Risner 1993, 1994; Risner and Nelson 1998). ETS yields have been determined from a number of compounds found primarily in the particulate phase. Table 1 lists those compounds and their yields (per cigarette) determined from a study of the top 50 brand-styles of cigarettes on the U.S. market in 1990 (Martin et al. 1997).

TABLE 1
Sales-Weighted Average ETS Yields of Gas-Phase Components Determined from Top 50 U.S. Brand-Styles*

Compound	Yield (µg/cigarette)
RSP†	13,700
Solanesol†	410
Scopoletin†	18.2
Catechol†	11.2
Carbon Monoxide	55,100
Total Hydrocarbons (by FID)	27,800
TVOC (Sorbent Tube)	19,100
Isoprene	6,200
Ammonia	4,100
Acetaldehyde	2,500
Nitric oxide	1,650
Nicotine	1,590
Formaldehyde	1,330
Acetonitrile	1,140
Acetone	1,070
Toluene	500
1,3-Butadiene	370
3-Ethenylpyridine	333
Benzene	280
Limonene	269
Pyridine	218
Nitrogen Dioxide	198
m-Xylene	176
3-Picoline	125
Styrene	94
Ethylbenzene	80
2-Picoline	75
p-Xylene	63
o-Xylene	59
Myosmine	49
3-Ethylpyridine	43.8
4-Picoline	39.5
1,2,3-Trimethylbenzene	33
1,3,5-Trimethylbenzene	13.8
n-Propylbenzene	8.5
Isopropylbenzene	5.1

* Martin et al. 1997.
† Particulate-phase component

Relatively few data are available for the generation of ETS by cigars. In a recent survey (Nelson et al. 1997b), ETS-RSP generated by six different cigars ranging from an inexpensive drug-store brand to a premium brand was examined (Table 2).

TABLE 2
ETS Yields from Cigars for Selected ETS Components*

Compound	Average (mg/cigar)	Range (mg/cigar)
Respirable Suspended Particles (RSP)	50	30 - 94
Carbon Monoxide	432	321 - 610
Total Hydrocarbons (FID)	340	267 - 394
Nitric Oxide	10.5	8.7-13.0
Nitrogen Dioxide	2.1	1.8 - 2.3

* Nelson et al. 1997b.

There are many potential sources of particles in an indoor environment other than ETS. One mistake sometimes made in indoor air investigations is to assume that all the particles present in an environment where smoking occurs originate from ETS. Although ETS can be a significant and even predominant source of particles in a given space, accurate apportionment of particles to ETS requires the use of particulate phase markers. The National Research Council outlined a number of properties that any ETS marker should possess (NRC 1986).

A number of factors can lead to a removal of particles from the air at a different rate than that seen for gases (Rodgman 1992; Nelson 1997a). For that reason, it is imperative that markers for the particulate phase rely on compounds found within the particles or properties of the particles themselves. The three most widely used particulate markers for ETS are ultraviolet particulate matter (UVPM), fluorescent particulate matter (FPM), and solanesol (Nelson et al. 1997c). Scopoletin and +α-tocopherol have also been advanced as potential ETS particulate markers (Risner 1994; Risner and Nelson 1998). UVPM, and to a lesser extent FPM, respond to some non-ETS types of combustion particles (Curl et al. 1995). Of the three commonly used markers, only solanesol is uniquely present in particles from ETS (Ogden and Maiolo 1989).

Historically, a wide range of ETS particle concentrations have been measured in indoor environments. Much of the variation may be due to the variety of environments and conditions under which samples were obtained. For example, Oldaker et al. (1990) reported a geometric mean ETS-RSP (by UVPM) concentration of 36 $\mu g/m^3$ for 82 restaurants in three cities and 27 $\mu g/m^3$ in 125 offices in four cities. Those measurements were typically performed in the smoking sections of restaurants during high occupancy periods, when smoking was known to take place, and in offices where smoking was observed to take place. Single-room taverns are one environment in which typical ETS concentrations may be higher. For example, Jenkins et al. (1997) reported that the median concentration in such establishments was 122 $\mu g/m^3$ by FPM. On the other hand, in the largest and most representative ETS exposure study performed to date, Jenkins et al. (1996) found that, based on UVPM, the typical concentration of ETS that nonsmokers were exposed to in the workplace over an eight-hour period was 10.9 $\mu g/m^3$ (arithmetic mean) and 4.13 $\mu g/m^3$ (median), with the 95th percentile at 82.6 $\mu g/m^3$.

Vapor-Phase Compounds

The vapor phase of ETS consists of gases formed by the combustion and pyrolysis of organic material within the cigarette and by the direct volatilization of tobacco leaf components. Table 1 summarizes the sales-weighted average yields of selected gas-phase components found in ETS (Martin et al. 1997). As is the case with particles, relatively few gas-phase analyte data are available for cigars. Table 2 includes ETS yields for several gas-phase analytes and the range of values obtained from a survey of six different cigars (Nelson et al. 1997b).

Most of the vapor-phase compounds associated with ETS have other sources in the environment. To accurately determine the fraction of a given component in an indoor environment that is associated with smoking, it is necessary to use a vapor-phase ETS marker that varies in constant proportion to the component being apportioned.

The preferred, and currently most widely accepted, quantitative gas-phase ETS marker is 3-ethenylpyridine (3-EP). 3-EP is a product of nicotine pyrolysis, or thermal degradation, and is unique to tobacco smoke. Its concentration tracks the concentrations of other gas-phase ETS components better than that of nicotine (another commonly measured ETS component) (Hodgson et al. 1997; Nelson et al. 1992a, 1997a). Heavner et al. (1992, 1996) and Hodgson et al. (1997) have detailed the use of 3-EP as a quantitative marker to apportion gas-phase analytes to ETS or other sources.

The first ETS gas-phase marker identified was nicotine. Subsequent studies on the use of nicotine as a gas-phase marker have shown it to be a relatively poor ETS marker. Although nicotine is commonly measured in association with smoking, its chemical properties cause it to behave differently in indoor air than other smoke components (Baker et al. 1988; Bayer and Black 1986; Guerin et al. 1992; Nelson et al. 1990; Oldaker et al. 1989). Unlike most other gas-phase ETS components, nicotine strongly adsorbs to many surfaces (Piadé et al. 1996; Van Loy et al. 1997) and can later desorb from surfaces in the absence of ETS giving the false impression that ETS is present.

Two other compounds that might initially appear to be potential markers for ETS, carbon monoxide (CO) and carbon dioxide (CO_2), are actually poor markers because they show poor specificity for ETS. On average, most of the CO in indoor air will have outdoor air as its source. Even if ETS elevates CO to relatively high levels, it is difficult to determine an appro-

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TABLE 3
ETS-RSP Levels, Number of Cigarettes Continuously Burned During Plateau and Average Ventilation Rate for Controlled ETS-Exposure Study*

Condition	ETS-RSP Level	Number of Cigarettes Continuously Burning During Steady State	Ventilation Rate (L/s)	Ventilation Rate (cfm)
1 (control)	0	0	235	489
2	58	1	648	1373
3	113	1	322	682
4	217	1	171	362
5	368	1	102	216
6	765	2	102	216

* Walker et al. 1997

priate background CO concentration to use in apportioning the fraction of CO, and, hence, other compounds, due to ETS. Although carbon dioxide (CO_2) is a major combustion product from the burning of cigarettes, it is even less useful than CO as a surrogate for ETS because there are many other sources of this compound in indoor air (particularly expired CO_2 from occupants).

SENSORY ISSUES

The chemical complexities of ETS noted above should be kept in mind when considering the relationship between ETS concentration and degree of impact on smokers or nonsmokers. Variability of ratios among particle and gas-phase compounds makes it difficult to develop agreed-upon definitions of ETS concentrations. In recent years, however, there has been a consensus reached that a reasonably good compromise is to specify ETS concentration in terms of ETS-attributable RSP. Adoption of ETS-RSP as a working definition of ETS concentration makes it possible to integrate various laboratory studies of the sensory impact of ETS to concentrations of ETS actually found in indoor environments. As discussed recently by Walker et al. (1997), this integration likely yields an overestimation of the sensory impact of ETS on nonsmokers. Thus, it should be possible to take concentration-response functions from such studies and develop (based on field-sampling data) a conservative estimate of the impact that should result from various environments in which different ETS concentrations are present. Based on a number of considerations recently discussed by Walker et al. (1997), and on data presented by Winneke et al. (1984), it is likely that such a process should actually over estimate the sensory impact of ETS.

Acceptability of ETS in Laboratory Studies

In a recently reported controlled laboratory exposure study, perceptual, eyeblink, breathing, psychological, and cognitive measures were used to quantify the effects on nonsmokers of a range of ETS concentrations ranging from 58 to 765 µg/m^3 (Walker et al. 1997). Table 3 shows the ETS levels attained and ventilation conditions for that study.

Figure 1 shows the mean increments in the ratings, from the pre-smoking baseline to the smoke plateau period, for a number of sensory attributes. The highest possible rating on each of these attributes was 60. A rating of 40 would signify that the magnitude of sensation was equal to the maximum intensity of this sensation ever experienced prior to the experiment. This figure confirms a finding that has been replicated in virtually every controlled laboratory exposure study of ETS or sidestream smoke: for any given concentration of ETS, odor ratings are the highest of all sensory attributes (well above the ratings for either eye or nasal irritation). This predominance of odor was progressively more apparent as the concentration of ETS was lowered.

The relative magnitudes of odor, eye irritation (the second most sensitive endpoint), and nasal irritation varied with ETS-RSP concentration. The three remaining attributes in Figure 1

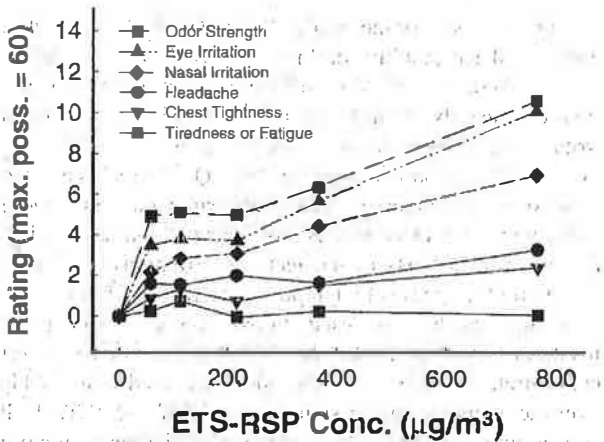

Figure 1 *The increment in ratings for several attributes over the values recorded in the no-smoking CONTROL condition (Walker et al. 1997).*

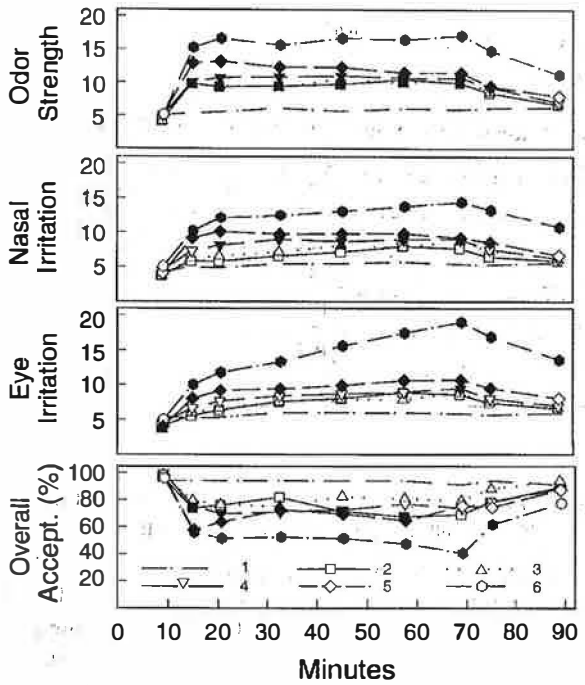

Figure 2 *Average ratings of odor strength, nasal irritation, eye irritation, and overall acceptability throughout the session (Table 4). The percentage of subjects indicating that the room air was acceptable is shown in the bottom panel. At each of the nine time points, ETS levels significantly different from the no-smoking CONTROL condition (1) are denoted with filled symbols (Walker et al. 1997).*

represent adverse symptoms and are much less effected than the sensory measures.

Figure 2 shows the ratings for three sensory attributes, and overall acceptability, during the session. With the highest ETS-RSP concentrations of 765 µg/m^3, perceived eye irritation rose steadily during exposure (20-70 minutes), but nasal irritation and overall acceptability exhibited much less evidence for temporal integration. In IAQ research, visitors to an indoor environment are typically assumed to be the more sensitive judges of odor (since odor adaptation has not had time to occur) but to be poor detectors of irritation (since insufficient time has passed for temporal integration to be evident). The same logic has been used to favor occupants as judges of irritation. However, the data in Figure 2 (for all but the highest concentration) show that perception remained quite stable over the course of the session for conditions 2-5 (ETS-RSP concentrations of 58 to 368 µg/m^3). This finding is in close agreement with that of Clausen et al. (1985). This failure to observe an effect of exposure duration calls into question the validity of preferring visitors or occupants in IAQ investigations.

The stability of odor and irritation response (Figure 2) over time for a given ETS-RSP concentration supports the acceptability of the room air as a reasonable measure of perceived indoor air quality. Acceptability has been used in the past by ASHRAE as a determinant of indoor air quality and it is incorporated into *ANSI/ASHRAE Standard 62-1989* (ASHRAE 1989). Acceptability of air quality is likely to reflect all or most of the kinds of short-term effects that ETS might have on an individual. Finally, the concept of acceptability is at the foundation of the decipol-olf approach advocated by Fanger (1988) as a means of quantifying occupant-defined indoor air quality.

An apparent additional advantage of using the acceptability measure is that its relationship to ETS-RSP concentration appears to be surprisingly robust over the course of different studies conducted over different periods of time. That is, similar results are obtained when different groups of subjects are tested using different experimental paradigms and in studies conducted at least a decade apart. Figure 3 shows the percent of acceptance (percentage of respondents rating air quality as acceptable) as a function of ETS concentration from a previous research study (Cain et al. 1983; Leaderer et al. 1984). Also shown in Figure 3 are the declines in percent of acceptance with increases in ETS-RSP concentration, from Walker et al. (1997). Results are quite similar for the two sets of data. Regression analyses showed that with the earlier data reported

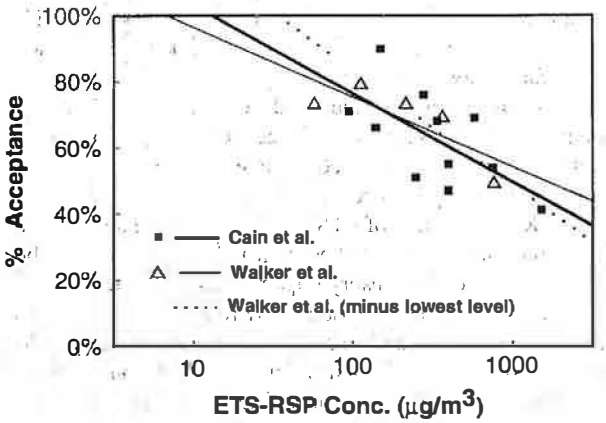

Figure 3 *Acceptance data from Walker et al. (1997), Cain et al. (1983), and Leaderer et al. (1984) are plotted as a function of ETS-RSP concentration. For the work of Cain et al., the 11 data points represent the responses of visitors during smoking, under conditions of moderate RH. Corresponding total suspended particles concentrations were retrieved from Leaderer et al. (1984) and were treated as ETS-RSP concentrations. Regression lines are shown for the work of Walker et al., with and without the lowest ETS level excluded, and for the work of Cain et al.*

by Cain and colleagues, 80% acceptance is first achieved at 74 $\mu g/m^3$, while the Walker et al. data indicate a value of 63 $\mu g/m^3$ (or 103 $\mu g/m^3$ if one excludes data for Walker's lowest level, for which the overall acceptance data were discontinuous from the remaining four levels). The continuity of results from the two studies suggests that the judgments of room air acceptability recorded in such studies are relatively unaffected by changing societal attitudes about smoking and ETS. It should be emphasized that these data are for nonsmokers tested in the controlled laboratory exposure paradigm. There is good evidence that smokers are far less responsive to ETS than nonsmokers (Cain et al. 1983; Walker et al. 1988; Clausen 1988).

A second important factor to be considered when applying results such as those in Figure 3 to the regulatory or policy arena is the finding (e.g., Winneke et al. 1984) that individuals are much less responsive to ETS in actual real-world environments than in laboratory exposures. This was also discussed recently in some detail by Walker et al. (1997).

Odor

The compounds present in ETS that are responsible for its odor are not clearly known. No single component, such as nicotine, is likely to be solely responsible or necessary for the odor associated with ETS. Odorous compounds are likely to consist of both volatile and semi-volatile materials.

Cain and others have suggested that acceptability is largely an inverse function of the odor of ETS. This is in agreement with the data shown above in Figures 1 and 2, which also indicate that, with concentrations progressively lower than ~ 400 $\mu g/m^3$, the primacy of odor (assuming the stimulus is detectable at all) will be even more apparent.

One interesting and relevant advance in odor science is the determination that the magnitude of odor sensation grows proportionally to the logarithm of odorant concentration. While knowledge of this log-normal metric is useful as a first step in attempts to apply human odor perceptual data to understanding the ETS/ventilation/odor question, there are a number of rather serious issues that greatly inhibit the use of published human olfactory data in this way. Relative to the number of compounds present in ETS, there are only a small number of compounds for which olfactory psychophysical parameters have been reported (Walker and Jennings 1991). Equally important, however, is the problem of inter-laboratory variation in one of the simplest measures of performance: odor detection threshold (Devos et al. 1990). The inter-laboratory variation is likely a result of inadequate attention to both the accuracy with which odorant stimuli are generated and an insufficient number of stimulus trials used to estimate sensitivity. The same factors likely account for the generally held view that there is an extremely wide variation in sensitivity within and among individuals (Burdach et al. 1985; Lawless et al. 1995; Stevens et al. 1988). This view may not be correct based on recent work (Kendal-Reed et al. 1998) indicating that intra- and inter-individual variation are far less than prior reports have suggested.

With a few recent exceptions (e.g., Laing et al. 1994), there has been little direct and quantitative examination of how mixtures of odorants are perceived. This is an important deficit in the literature. In indoor air, regardless of the presence of ETS, individuals are exposed to a complex mixture of odorants. The small amount of data available are, however, in general agreement in suggesting that the perceived intensity of mixtures is less than would be predicted if perceptually equivalent concentrations of a single odorant were simply added together. To illustrate, imagine three odorants, A, B, and C, adjusted in concentration to be equally perceptually intense. From work thus far, it would be predicted that an A+B+C mixture will have a weaker odor than any of the three odorants alone presented at a three fold higher concentration.

Irritation

As noted above, there is little reason to think that eye or nasal irritation is as important as odor perception in determining responses to ETS at environmentally realistic concentrations. Based on the integration of field and laboratory data, for example, it seems extremely likely that a large proportion of exposures to ETS will result in odor perception that ranges from nonexistent to weak or moderate but will not result in detectable levels of eye or nasal irritation. Nonetheless, there are likely to be some situations where there is some perception of eye and/or nasal irritation. For this reason, some basic comments as to what is known about each are included below.

With respect to nasal irritation, the paucity of quantitative data on human sensitivity is even more pronounced than with odor. One prominent laboratory (e.g., Cometto-Muñiz and Cain 1990; Cometto-Muñiz and Cain 1994; Cometto-Muñiz and Cain 1995) has taken the approach of using only anosmic individuals to measure nasal irritation based on their observation that individuals with both olfactory and trigeminal systems intact may experience some difficulty or uncertainty in reporting this sensation. While this approach undoubtedly removes the potentially distracting influence of odor perception, it also has the problem of omitting from the study the possible role of olfactory nerve stimulation in perceived nasal irritation. Participants in odor psychophysical studies are seldom asked to rate the presence or degree of nasal irritation. Only a few studies have quantified the nasal irritation sensitivity of normal individuals (Walker et al. 1990; Kendal-Reed et al. 1998; Prah and Benignus 1984; Shams Esfandabad 1993).

Still fewer data are available with regard to eye irritation. Cometto-Muñiz and Cain (1995), Kjaergaard and Pedersen (1989), and others have measured responses to a variety of known or suspected ocular irritants. The information presented has been of significant but somewhat limited value, however, due to the methodology employed to test a wide variety of compounds on a large number of individuals: variable volumes from the headspace of puff bottles delivered by the

participant's squeezing of the bottles and presented for variable durations. There remains a need to measure both breathing and perceptual responses to precisely controlled concentrations of chemicals (both single compounds and mixtures) delivered to the eyes for a wide range of durations. It should be noted that there have been a number of careful studies over the past three decades on the physiological and biochemical aspects of chemoreceptor responses from the corneal surface (e.g., Dawson 1962; Beuerman and McCulley 1978; Tanelian and Beuerman 1982; Tanelian 1991) in response to a range of stimulus intensities far below those typically required to produce a detectable effect on the Draize scale (Draize et al. 1944). It is likely that these reports, particularly when considered together with comparable studies of the biology of nasal trigeminal responses (e.g., Silver 1990), will shed light on the responses to corneal stimulation.

DILUTION VENTILATION RATES FOR THE SIMPLIFIED CASE

From the previous section, it is clear that irritation, odor, and acceptance vary as a function of concentration for a variety of substances including ETS. When there is generation of a compound in an indoor environment, there needs to be a removal mechanism to limit the concentration. One special mechanism is direct exhaust, such as a fireplace, chimney, or kitchen range exhaust hood. For general removal, however, occupied spaces have an air exchange with the outside through either mechanical or natural ventilation and infiltration.

The simplified case discussed below also uses ventilation for removal, with the following conditions:

- a single volume of air is well mixed;
- there are steady-state conditions (generation rate and ventilation rate are constant);
- the assumption is that there is no filtration, deposition, or emission of the substance of interest from surfaces.

The physical model for the relationship between concentration, ventilation, and generation is:

$$C_i = C_{r0}e^{-(Q_{oa})t/V} + \frac{C_o Q_{oa} + S}{Q_{oa}}(1 - e^{-(Q_{oa})t/V}), \quad (1)$$

where

t = time (h),
C_i = concentration (µg/m^3),
C_{r0} = concentration in room at time = 0 (µg/m^3),
C_o = concentration in intake air (µg/m^3),
Q_{oa} = ventilation rate (m^3/h),
V = volume (m^3),
S = generation rate (µg/h).

At steady-state, $t \to \infty$ and Equation 1 is reduced to

$$C_i = C_o + \frac{S}{Q_{oa}}. \quad (2)$$

Under controlled laboratory conditions, C_o is either controlled to a value of zero (as in filtration of particles) or is carefully measured and corrected as background (as in the case of background CO). Under steady-state laboratory conditions, the concentration term becomes

$$C_i = \frac{S((\mu g)/h)}{Q_{oa}(m^3/h)} = \frac{\mu g}{m^3} \quad (3)$$

and can be expressed in terms of a single variable, the dilution volume (D [m^3/cigarette]), if one assumes that cigarettes generate a known constant mass of substance (M_i [µg/cigarette]).

$$C_i = \frac{M_i(\mu g/cig)}{D(m^3/cig)} = \frac{\mu g}{m^3} \quad (4)$$

Laboratory Test Results

In the controlled laboratory setting used to measure acceptance and odor from ETS, different conditions were created by varying both the rate of smoking and the amount of dilution air. Equations 3 and 4 can be used to calculate dilution volumes from those laboratory studies. Leaderer and Cain (1983) measured per cigarette dilution volumes and concluded that 78 m^3 - 120 m^3 (2800 ft^3 - 4200 ft^3) per cigarette would place acceptability at about 75% to 80%. Using Equation 4, the dilution volume from Walker et al. (1997), corresponding to 79% acceptance, is 116 m^3 (4100 ft^3) per cigarette.

As previously noted, the response of smokers to ETS differs from that of nonsmokers. A possible dilution volume for smokers for 80% acceptance can be estimated from the data presented in Figure 4. Note that Straub et al. (1993) varied air distribution patterns in a model smoking lounge and measured acceptability of the air quality by smokers. Based on a generation of 13,700 µg ETS-RSP per cigarette (Martin et al. 1997) and assuming steady-state and well-mixed conditions, one can use Equation 4 to compute a range of 25 m^3 - 40 m^3 (880 ft^3 - 1410 ft^3) as the amount of dilution required per cigarette. This range is shown as an oval in Figure 4.

ANSI/ASHRAE 62-1989 (General Case)

If one assumes that the design dilution values for approximately 80% acceptance in a laboratory chamber-type setting are 78 m^3 - 120 m^3 (2750 ft^3 - 4240 ft^3) for nonsmokers and 30 m^3 - 40 m^3 (880 ft^3 - 1410 ft^3) for smokers, then four cases listed in ASHRAE Standard 62-1989 can be derived (Table 4) with the following assumptions:

1. The dilution values can be extrapolated from the available study data.
2. Smoking will occur over a long time period so that steady-state conditions are calculated.

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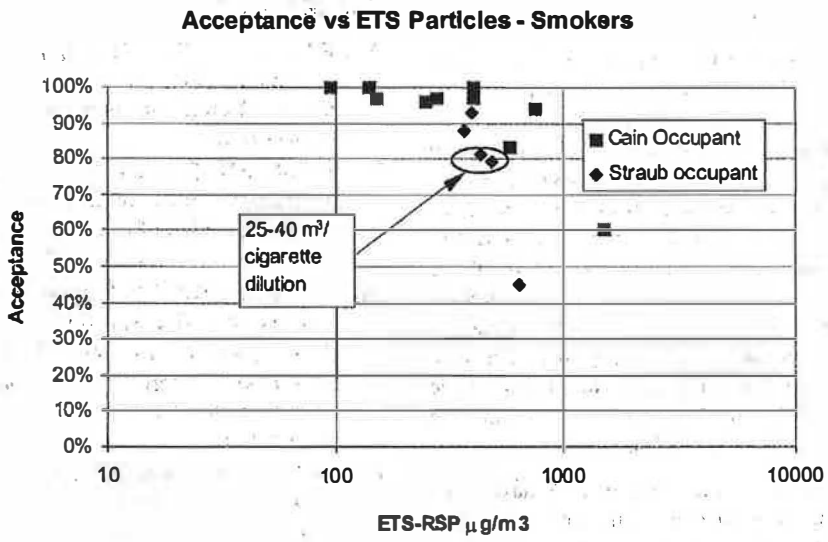

Figure 4 *Acceptance data from Straub (1993) and for Cain (Cain et al. 1983; Leaderer et al. 1984) are plotted as a function of ETS-RSP concentration. For the Cain research, the data points represent the responses of occupants during smoking, under conditions of moderate RH. Corresponding TSP concentrations were retrieved from Leaderer et al. (1984) and were treated as ETS-RSP concentrations. For the Straub research, the data points represent the responses of occupants during smoking, under various air distribution conditions, and corresponding ETS-RSP concentrations were obtained from Nelson et al. (1992b).*

3. The air in the space is well mixed.
4. The number of smokers in the space is the national average.
5. The smokers smoke at average rates.

Assumption 1 is conservative since the results of Winneke (1984) suggest that acceptability of the air in the real world would be higher than in the laboratory; as a result, acceptability would be predicted to occur at dilution volumes below those predicted by laboratory experiments. Assumption 2 is also conservative; e.g., if cigarette-smoke concentrations are below steady-state value, acceptability should increase. The third assumption is explicitly stated as a part of *ANSI/ ASHRAE Standard 62-1989* (ASHRAE 1989). Results of the model will be normalized by assumptions 4 and 5. That is, they should make the predicted dilution rate apply to the average situation in which smoking takes place. When the conservative and normalizing assumptions are combined with empirical data (laboratory dilution volumes), remarkably good agreement between the amount of fresh air specified by the model and the volume of fresh air specified in Standard 62-1989 is observed. Fresh air delivery rates specified in the standard are within the range predicted by the model to be necessary to achieve acceptability (Table 4).

TABLE 4
Derivation of Rates in ASHRAE Standard 62-1989.
Percent Smokers and Smoking Rates from Janssen (1991)

Location	Office	Restaurant	Bar	Smoking Lounge
Smokers	27%	27%	27%	100%
Cigarettes/ h	1.25	1.25	2	3
Cigarettes/ h-person	0.34	0.34	0.54	3.00
Dilution Volume, m^3	78- 120	78- 120	78- 120	25-40
Dilution Volume, ft^3	2750-4240	2750-4240	2750-4240	880-1410
Ventilation rate, L/s	7.3- 11.3	7.3- 11.3	12-18	21-33
Ventilation Rate, cfm	15-23	15-23	23-36	42-67
ASHRAE 62-1989	20	20	30	60

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SUMMARY

Environmental tobacco smoke, 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 (lit-end) and exhaled mainstream smoke. The gas and, to a lesser extent, the particulate-phases of ETS have been characterized, and emission factors for a wide range of ETS components are available in the literature. Methods to predict exposure to non-ETS specific compounds through the use of markers is also readily available. The specific compounds associated with the odor of ETS are not known. Attempts made to duplicate the odor suggest that a large number of components contribute to this odor. It is possible that the odor is due in part to semi-volatile compounds that slowly volatilize from the ETS particles.

Many of the compounds identified in ETS have other indoor sources. To apportion the contribution of ETS to these compounds in indoor air, one must measure marker compounds. As a result of differences in the interaction of the gas and particulate phases with interior surfaces, including HVAC systems, it is preferable to use separate markers for the gas and particulate phases of ETS. The three most commonly used particulate markers, in order of increasing specificity, are UVPM, FPM, and solanesol. Among the commonly used gas-phase markers of ETS, nicotine concentrations do not track well the concentrations of most other measurable ETS components. The current best marker for the gas phase of ETS is 3-ethenylpyridine.

Experiments performed in controlled laboratory settings suggest that odor is the primary factor associated with sensory evaluation of ETS in the air, at least at concentrations corresponding to less than 400 $\mu g/m^3$ ETS-RSP. Acceptability of ETS varies among people. Data available in the literature suggest that smokers find air quality acceptable at higher concentrations than nonsmokers. Among nonsmokers, 80% acceptability of air quality is achieved at ETS levels resulting in ETS-RSP concentrations of about 60-100 $\mu g/m^3$. However, for a given ETS concentration, laboratory measurements of sensory impact likely overestimate the impact of ETS on nonsmokers in real-world settings. That is, 80% acceptability is likely to be achieved at higher concentrations in the field than those observed in the laboratory.

When combined with published data on smoking rates, results from laboratory studies on the impact of ETS on nonsmokers and the chemistry of ETS can be used to generate a simple model of acceptability as a function of source strength and ventilation. Such a model can be used to predict the appropriate dilution volume needed to achieve 80% acceptability in the field. When the model is used to calculate dilution values for commonly encountered smoking situations, the resulting dilution volumes and ventilation rates are generally consistent with those published in Standard 62-1989.

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