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VENTILATION REQUIREMENTS IN OCCUPIED SPACES DURING SMOKING AND NONSMOKING OCCUPANCY

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Ventilation requirements in occupied spaces have traditionally derived largely from odor control. The requirements have rested on the notion that an environment that seems subjectively acceptable to a visitor will in fact be healthful and comfortable for both visitor and occupant alike. Ventilation requirements have derived secondarily from criterion concentrations of notable contaminants (e.g., carbon dioxide). The present investigation looked again at both sensory (odor, irritation) and physical criteria of acceptability, paying particular attention to the difference between smoking and nonsmoking occupancy in a well-controlled environmental chamber. More than 200 persons (visitors) made judgments of odor intensity and acceptability under various conditions of occupancy (up to 12 nonsmoking occupants; a temperature of up to 25.5 °C; up to 16 cigarettes smoked per hour). The results implied that under nonsmoking conditions and moderate humidity only about 7.5 cfm (3.8 Lsec^{-1}) of fresh air per occupant sufficed to satisfy visitors, but that under smoking conditions at least 5 times as much fresh air is necessary. Our estimate of ventilation requirements for smoking were derived in part from measurements of carbon monoxide and total suspended particulate (TSP) mass concentration. Levels of TSP achieved during realistic smoking and ventilation rates exceeded levels deemed acceptable outdoors. Surfaces in the chamber played an important role in the elimination of particles, presumably via adsorption. Use of an electrostatic precipitator could keep TSP levels under control. Nevertheless, it remains to be seen whether control of TSP will eliminate the need for enormous ventilation for odor control during smoking occupancy.

Introduction

In the general absence of any better or faster indicator, smell will serve as the principal means for a visitor to decide whether the air in a room is acceptable. Accordingly, this modality has long figured directly or indirectly in the choice of ventilation rates. In the 1930's, there arose the notion that a quantitative criterion for tolerable occupancy odor could determine the need for ventilation. Various researchers, but principally Yaglou, applied simple psychophysical scaling to the question of how the level of occupancy odor perceived by visitors to a room depended on ventilation. In the most ambitious study, Yaglou *et al.* (1936) charted odor as a function of density of occupancy (i.e., number of people in a room), age, personal hygiene, and ventilation rate, ranging from 5 cfm (2.5 Lsec^{-1}) per occupant to 30 cfm (15 Lsec^{-1}) per occupant. Although all of these factors had some influence on odor, the most important factor, and most widely cited outcome, was the relationship between odor level and density of occupancy (Fig. 1). In order to hold odor at a moderate level (2 on a scale of 0 to 4), the amount of ventilation necessary increased disproportionately with the number of persons in a room. For instance, as the number of people in Yaglou's chamber increased from 3 to 7, the required amount of fresh air per occupant increased from 7 cfm (3.5 Lsec^{-1}) to 16 cfm (8 Lsec^{-1}). For 14 occupants, the required amount of fresh air equalled 25 cfm (12.5 Lsec^{-1}) per occupant.

Few persons have argued that Yaglou's recommended rates fall *below* that required for sedentary, nonsmoking occupancy. During the time that energy has increased rapidly in price, some have wondered whether the recommended rates fall *above* those necessary, particularly in moderately crowded spaces such as classrooms, conference rooms, and waiting rooms. In an effort to build upon previous psychophysical work, we built an environmental chamber for the exploration of ventilation requirements to control occupancy odor and tobacco smoke odor. Despite the prevalence and severity of tobacco smoke as a nuisance, ventilation requirements for it have received scant attention.

Combustion of tobacco generates a large variety of

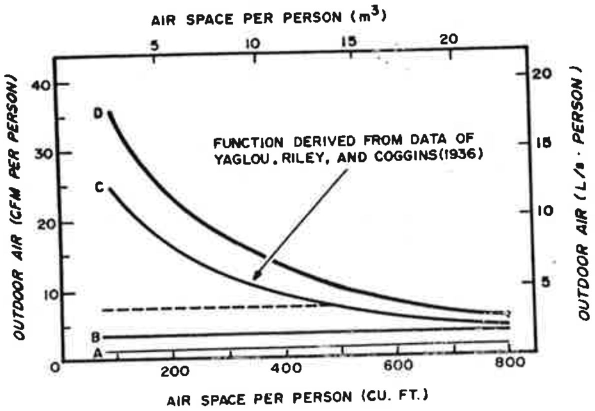

Fig. 1. The relation between air space per person and ventilation requirements under various criteria: Curve *A*: maintenance of sufficient oxygen ($\geq$ 20%); curve *B*: control of carbon dioxide ($\leq$ 0.6%); curve *C*: control of odors during sedentary, nonsmoking occupancy (data of Yaglou and colleagues); curve *D*: control of odors during smoking occupancy (arbitrary 50% upward transposition of curve *C* without supporting data). We have added to this well-known figure the requirements based on occupancy odor from the present experiments (dashed line).

organic and inorganic chemicals in both the gaseous and particulate phases. The nature of the emissions will vary, depending upon such factors as brand of cigarettes, temperature of combustion, smoldering rate, frequency of puffs, depth of inhalation, etc. The "mainstream" combustion products resulting from cigarette smoking are associated with adverse health effects in smokers, e.g., chronic obstructive lung disease and lung cancer (USDHEW, 1979). There has been increasing concern that exposure to "sidestream" smoke in enclosed spaces may also pose some risk to nonsmokers (Wynder and Hoffmann, 1979; White and Froeb, 1980). Any efforts to reduce ventilation rates in occupied spaces in order to conserve energy may amplify the presence of sidestream contaminants indoors. Since about 30% of the adult American population smokes cigarettes at an average rate of about 2 cigarettes/h (Jaffe, 1978), and since most persons spend 70%–90% of their time indoors (Szalai, 1972), the potential exposure to sidestream smoke is great.

The experiments reported below focused on concentrations of certain notable contaminants as well as on odor. Concern with odor derives primarily from the need to satisfy the visitor to a space, whereas concern with contaminant levels derives from the need to protect the occupant. We have given some attention to the sensory reactions (odor, irritation, and thermal sensations) of occupants as well as the reactions of visitors, but these studies fall beyond the scope of the present paper. The contaminants of interest included total suspended particulate matter (TSP) and carbon monoxide (CO). Ambient air quality standards for these two pollutants have been established by the U.S. Environmental Protection Agency (EPA) and the standards can serve as a reference for assessing indoor air quality during smoking. Regarding contaminant monitoring, the present paper will give special attention to (1) the relation between ventilation rate and level of TSP and CO in both dynamic and steady-state conditions, (2) the number and volume distribution of sidestream particulate emissions, and (3) the rate of removal of CO and TSP via adsorption by surfaces and an air cleaning device.

Method

Facilities and equipment

The experiments employed an aluminum-lined chamber of 1200 ft³ (34 m³) equipped with an ideal ventilation system that led to rapid mixing of outdoor air with contaminants generated in the chamber (Fig. 2). An important feature of the set-up included a sniffing station (0.11 m³) that allowed persons to judge the quality of the air in the chamber without the need to enter it. More than 200 persons participated in the psychophysical experiments.

Air flow through the chamber was laminar. The air flowed from a plenum beneath a perforated floor upward to the ceiling. Volume flow (recirculation rate) typically equalled 2000 cfm (1000 $L sec^{-1}$) or 100 air changes per hour (ach). Ventilation air brought into the chamber could vary from 0 to 400 cfm (0 to 200 $L sec^{-1}$) or 0 to 20 ach. The chamber possessed excellent temperature ($\pm$0.1 °C) and humidity control. Air cleaning could be accomplished by passing air through an electrostatic air cleaner or granular filter media, or both.

Carbon monoxide was monitored by means of an Energetics Science, Inc., Ecolyzer Model 2500. Total particulate mass was monitored with a Thermo-Systems, Inc., Model 3200A Particulate Mass Monitoring System. A RICH 100 Environment One Nuclei Monitor

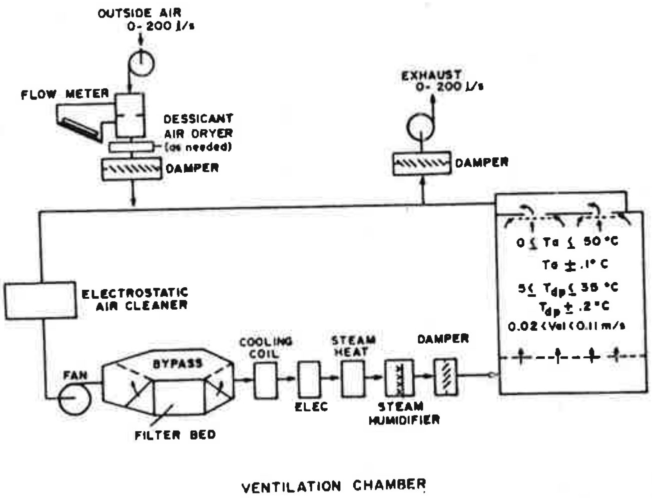

Fig. 2. Schematic view of environmental chamber and control equipment. Arrows in box at right portray the flow of air from the plenum beneath the floor to return ducts in the ceiling.

measured concentrations of condensation nuclei. The size distribution of tobacco smoke was assessed by means of a Thermo-Systems, Inc., Electric Aerosol Size Analyzer (Model 3030) for particle sizes 0.003–1.0 μm and a Climate Optical Particle·Counter (Model CI-225) for particle sizes 0.5 m–10.0 μm.

Psychophysical experiments

The main factors in the investigation of occupancy odor included three levels of occupancy (4, 8, and 12 occupants), four ventilation rates [5, 10, 15, and 20 cfm (2.5–10 $Lsec^{-1}$) per occupant], and four environmental conditions (20 °C, RH ≤ 50%, denoted moderate humidity; 23 °C, moderate humidity; 25.5 °C, moderate humidity; and 25.5 °C, RH ≥ 70%, denoted high humidity). Each of 47 combinations of these factors received attention and led to a function that described the way in which occupancy odor varied over a 60-min period of occupancy.

The main factors in the investigation of tobacco smoke odor included three rates of smoking (4, 8, and 16 cigarettes/h smoked by four smokers), six ventilation rates [11, 16, 20, 25, 35, and 68 cfm (5.5 to 34 $Lsec^{-1}$) per occupant], and four environmental conditions (20 °C, moderate humidity; 23 °C, moderate humidity; 25.5 °C, moderate humidity; and 25.5 °C, high humidity). Of the total possible combinations, 38 were studied. A given combination led eventually to a function that described how odor magnitude varied over a period that began with a 15-min segment of nonsmoking occupancy (presmoking segment), then continued with a 60-min segment of smoking, and ended with a 60-min segment of nonsmoking occupancy (postsmoking segment), for a total of 135 min.

The primary psychophysical judgement involved matching the intensity of one or another concentration of butanol [16–2048 ppm (μL/L) in 2:1 steps] to occupancy or tobacco smoke odor. The concentrations of butanol were made available from the eight nozzles (ports) of a Dravnieks binary-dilution olfactometer described in ASTM Standard E-544 (ASTM, 1975). This standard describes a procedure to measure suprathreshold odor intensity via matching. In principle, a person can always find a concentration of butanol that falls close to the perceived intensity of any given test odor.

At the beginning of a session, the participants made some practice judgments. Then persons designated as occupants entered the chamber for a period of smoking or nonsmoking occupancy. The remaining participants, designated as visitors, sat in a waiting room and proceeded one-by-one through an unoccupied 25-m corridor to the sniffing station, where they matched the test odor to a concentration of butanol. After a judgment, the visitor returned to the waiting room and told the next person in line to proceed to the sniffing station. Normally six to eight visitors participated in a session, and each person made about eight or nine judgments per hour. The given conditions were repeated on an irregular basis until we had judgments from about 25 visitors.

At the time of the final judgment of a period of smoking or nonsmoking occupancy, the visitor added an additional component to the estimate of odor intensity. This component involved circling one of two choices: "acceptable" or "not acceptable." These referred to the odor experienced only during the final exposure of a session.

Experiments on carbon monoxide and particulate matter

Two types of experiments were performed. The first consisted of monitoring CO and TSP during the course of the psychophysical experiments. This experiment allowed for a comparison of the relative effectiveness of ventilation and adsorption by surfaces as mechanisms for removal of CO and TSP. The comparison can be made from decay curves which resulted when smoking ceased after 75 min into the runs.

A second set of experiments evaluated (a) steady-state concentrations of CO and TSP during ventilation, (b) removal by surfaces after main ventilation had ceased but internal mixing continued via fans in the chamber, and (c) the effectiveness of an electrostatic air cleaner in removing TSP in the recirculated air. In these experiments, four occupants (all smokers) generally occupied the chamber. Fifteen minutes after entering, the occupants began to smoke at a prescribed rate. Ventilation rate was then decreased in steps from 272 cfm (136 $Lsec^{-1}$), or 68 cfm (34 $Lsec^{-1}$) per occupant, down to 44 cfm (22 $Lsec^{-1}$), or 11 cfm (5.5 $Lsec^{-1}$) per occupant. Ventilation rate was decreased only after CO and TSP had reached steady state. Each cigarette was smoked for 7.5 min at rates of 4, 8, 16, and 24 cigarettes/h. The occupants smoked one brand of cigarette: 85 mm in length and 17 mg in tar (FTC value). For those experiments conducted at 24 cigarettes/h, six persons occupied the chamber and three smoked at any given time. When the steady level of CO and TSP was reached for the condition 8 cigarettes/h at 44 cfm (22 L sec^{-1}), the occupants left the chamber, the ventilation rate was set to 0 cfm, a fan was used to insure mixing in the chamber, and the decay of CO and TSP was monitored. During some such experiments, the electrostatic air cleaner was put in line with the recirculated air after smoking had ceased. The resulting decays allowed an assessment of the effectiveness of surfaces and electrostatic air cleaners in removing TSP and of surfaces alone in removing CO under ideal mixing conditions.

Results

Psychophysical experiments

The data below deal only with highlights of this extensive investigation (Cain *et al.*, 1982; Leaderer *et al.*, 1982). Figure 3 contains butanol matching functions (port numbers on left ordinate, ppm or μL/L on right ordinate) showing how occupancy odor varied with time for three densities of occupancy (4–12 occupants in the chamber). Each function comprises four data points plotted at 15-min intervals. These particular functions were averaged across all four environmental conditions in order to determine how odor varies with the number of persons in the chamber. Each function summarizes observations from approximately 100 visitors. The outcome, unlike that of Yaglou *et al.*, implied no consistent effect of density. That is, a given ventilation rate per occupant seems to lead to approximately the same odor level regardless of how many persons occupied the chamber.

Figure 4 depicts results taken across number of occupants, thereby focusing on the influence of environmental conditions. This plot reveals only one systematic trend, namely, the tendency for the combination of high temperature and high humidity to generate more intense odor than conditions of moderate humidity. The average influence of high humidity amounted to 0.6 butanol scale units, an increment of 50% in matched concentration of butanol.

Under conditions of moderate humidity, even ventilation rates as low as 5 cfm (2.5 Lsec^{-1}) per occupant led to relatively mild odor (butanol level of 3.3). Such a level met rather high acceptance, as shown in Fig. 5. This figure summarizes all of the judgments of acceptance plotted as a function of the butanol match made roughly simultaneously. Although some persons failed to accept any discernible odor, between 70% and 80% accepted the odor levels achieved with ventilation rates between 5 and 10 cfm (2.5 and 5 Lsec^{-1}) per occupant. Such high acceptance prompts us to recommend a ventilation rate of 7.5 cfm (3.8 Lsec^{-1}) per occupant, even under the conditions of crowding. We suspect that accurate control over environmental conditions and actual measurement of ventilation rate (as opposed to a nominal calculation) can explain why our recommendation falls below Yaglou's under conditions of high density of occupancy.

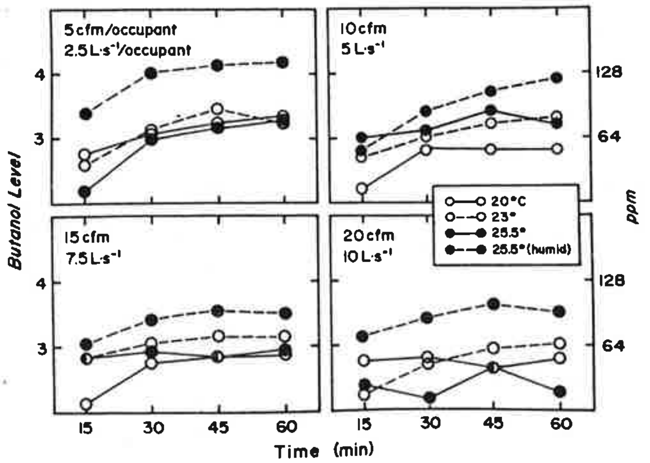

Fig. 4. Butanol matching functions taken across number of occupants in order to explore whether odor level varied systematically with environmental conditions. (ppm = μL/L.)

Figure 1 depicts how our recommendation of 7.5 cfm (3.8 Lsec^{-1}) per occupant would fit into the pattern of results obtained by Yaglou *et al.* (1936). The area between function *C* and the dashed line at 7.5 cfm (3.8 Lsec^{-1}) per occupant represents an opportunity for energy savings, provided that temperature and humidity control are adequate to prevent hot, humid conditions. Figure 1 also displays (curve *D*) recommendations for smoking occupancy added apparently by Viessman

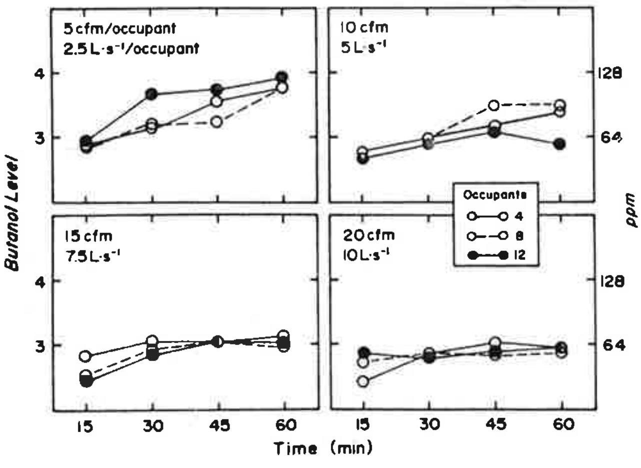

Fig. 3. Butanol matching functions taken across environmental conditons in order to explore whether odor level varied systematically with number of occupants at various ventilation rates ranging from 5 cfm to 20 cfm (2.5 to 10 Lsec^{-1}) per occupant. The term butanol level refers to the port number (1–8) of a Dravnieks olfactometer. Successively higher port numbers reflect twofold increments in concentration of butanol (ppm shown on right). (ppm = μL/L.)

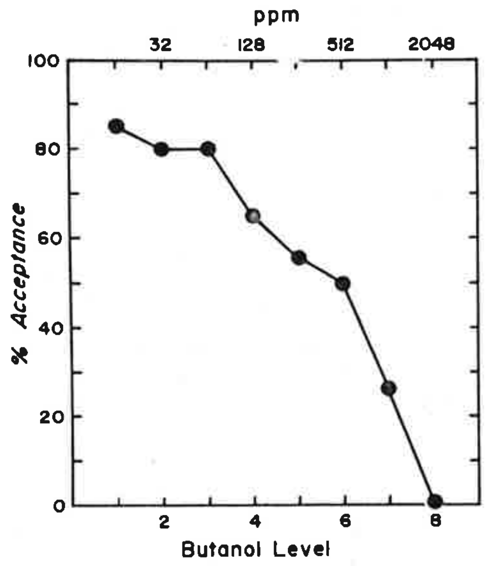

Fig. 5. Function showing how acceptance of occupancy odor to visitors varied with equivalent (i.e., matched) level of butanol. The judgments were accumulated across all conditions and show results for more than 900 participant-hours. (ppm = μL/L.)

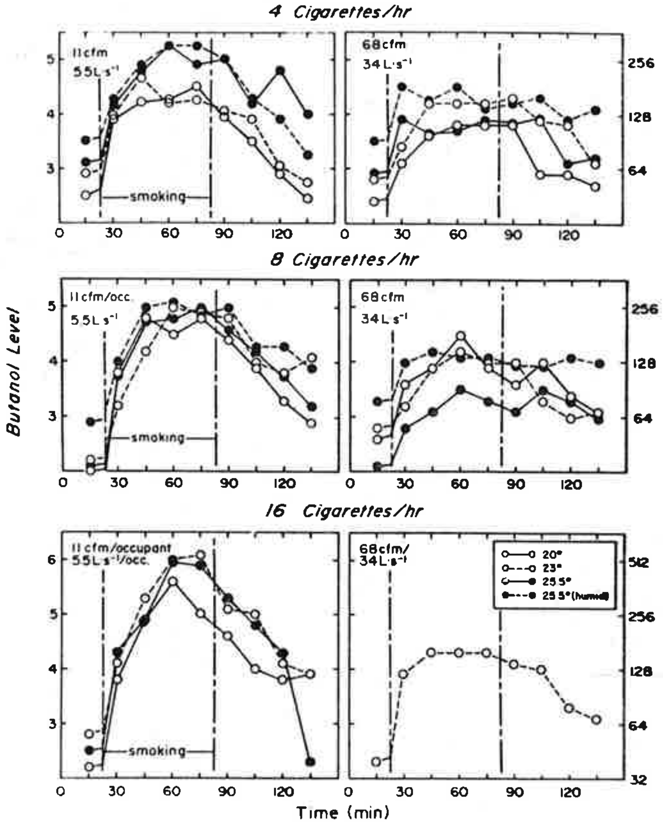

Fig. 6. Butanol matching functions obtained during the lowest and highest ventilation rates, 11 and 68 cfm (5.5 and 34 Lsec^{-1}) per occupant, respectively, in various environmental conditions. Butanol level (port number of olfactometer) is shown on left ordinate and ppm is shown on right ordinate. Smoking began in the interval between 15 and 20 min and ended in the interval between 75 and 90 min. These functions contain judgments from 25-30 participants and have standard errors of 0.25-0.33 butanol scale steps. (ppm = μL/L.)

(1964) about two decades ago but without supporting data. Our results on tobacco smoke odor imply that curve *D* generally falls below that needed.

Figure 6 shows how odor rose and fell over time for various combinations of smoking rate, ventilation rate, and environmental conditions. This figure depicts results only from the lowest and highest ventilation rates. Results from the other rates fell between those shown here. The matching functions span a substantial portion of the range of butanol levels. Butanol levels as high as 5 occurred routinely at the lower ventilation rates, whereas such levels never occurred in the study of occupancy odor.

Figure 7 displays odor intensity on the butanol matching scale normalized to percentages. The figure includes data for moderate humidity only. A scale value of 100% equals the intensity of presmoking occupancy odor. The normalization procedure rested on the assumption that the high ventilation rates used to combat cigarette smoking would control occupancy odor with relative ease, a situation that would therefore blunt any dependence of that odor on such high rates of ventilation. Figure 7 also contains, for reference, a function that depicts how magnitude of mere occupancy odor varied over time with a ventilation rate of only 5 cfm (2.5 Lsec^{-1}) per occupant (left panel). Note that tobacco smoke odor exceeded occupancy odor no matter how great the ventilation during smoking.

Dependence of odor on rate of ventilation displayed itself more strongly at 8 and 16 cigarettes than at 4 cigarettes/h. At the low rate of smoking, ventilation rates ranging from 11 to 68 cfm (5.5 to 34 Lsec^{-1}) per

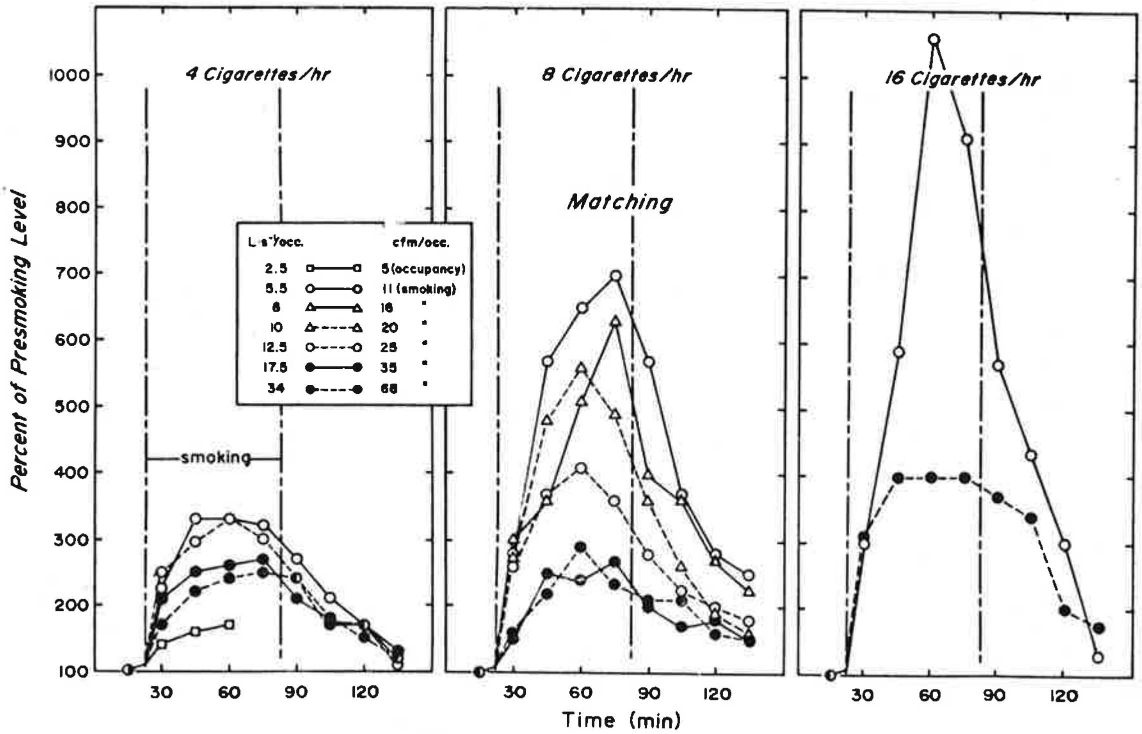

Fig. 7. Butanol matching functions averaged across conditions of moderate humidity and expressed as percentage of odor level (ppm butanol) (μL/L) achieved during 15 min of nonsmoking occupancy.

occupant led to similar odor levels. The reason for this outcome becomes apparent from measurements of the physical stimulus, a matter treated below. In brief, odor magnitude tended to lose any strong dependence on ventilation rate at those rates sufficiently high to prevent significant accumulation of contaminants from cigarette to cigarette. At a smoking rate of 4 cigarettes per hour, each cigarette emerged more or less as a separate peak in the minute-by-minute records of contaminants. Such individual peaks cannot reveal themselves in average psychophysical curves because of limitations in temporal resolution. Rather than peaks and troughs, the psychophysical data display a flattening generally characteristic of records that integrate episodic events.

The acceptance of tobacco smoke odor as a function of intensity (Fig. 8, left side) followed a pattern similar to that obtained previously with occupancy odor. In the present case, however, the generally high odor levels precluded high acceptance. Seen on a condition-by-condition basis, only two combinations of smoking rate and ventilation rate appeared acceptable to as many as 75% visitors during the period of active smoking. A criterion of 75%–80% acceptance was a realistic goal for occupancy odor, but not apparently for tobacco smoke odor.

Inclusion of both smokers and nonsmokers among the visitors permitted erection of separate acceptance functions for the two groups (Fig. 8, right side). As might be expected, nonsmokers set more stringent criteria for acceptance than smokers. In the critical region of 65%–80% acceptance, the difference between the functions amounted to a sizeable 3 butanol scale units. If the data yielded by the entire group had left any doubt about the need for enormous ventilation during smoking, that doubt should disappear with consideration of nonsmokers. None of the conditions in the present investigation would satisfy even two-thirds of nonsmokers.

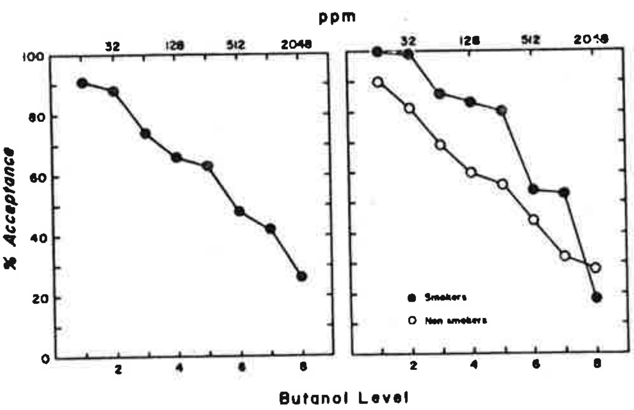

Fig. 8. Left: The relation between acceptance and intensity of tobacco smoke odor, expressed as butanol equivalent (butanol level on bottom abscissa, ppm on top abscissa). The data comprise the impressions of all visitors in all experiments and show results for more than 2300 participant-hours. Right: The relation between acceptance and odor intensity for smokers and nonsmokers separately. (ppm = μL/L.)

Physical correlates of the psychophysical experiments

Figure 9 shows how carbon monoxide (CO) attributable to smoking varied with time for various rates of smoking at the lowest and highest ventilation rates. In this and subsequent graphs, $t = 0$ min represents the point when smoking began. The curves for 4 cigarettes/h display a cyclicity associated with the regularity of the smoking, i.e., one cigarette every 15 min.

At smoking rates of 8 and 16 cigarettes/h, individual cigarettes did not show up as discernible peaks in the average records (Fig. 9). As in the case of 4 cigarettes/h, the curves continued to climb throughout the period of smoking whenever the ventilation rate fell below 25 cfm (12.5 $L sec^{-1}$). Even rates above 25 cfm (12.5 $L sec^{-1}$) exhibited some inability to eliminate growth by the end of the 1-h smoking period. Nevertheless, except in the case of the lowest ventilation rate, the concentration of CO seemed likely to remain within the limit specified by the national ambient air quality standard even if smoking had continued (see below).

Total suspended particulate (TSP) mass concentra-

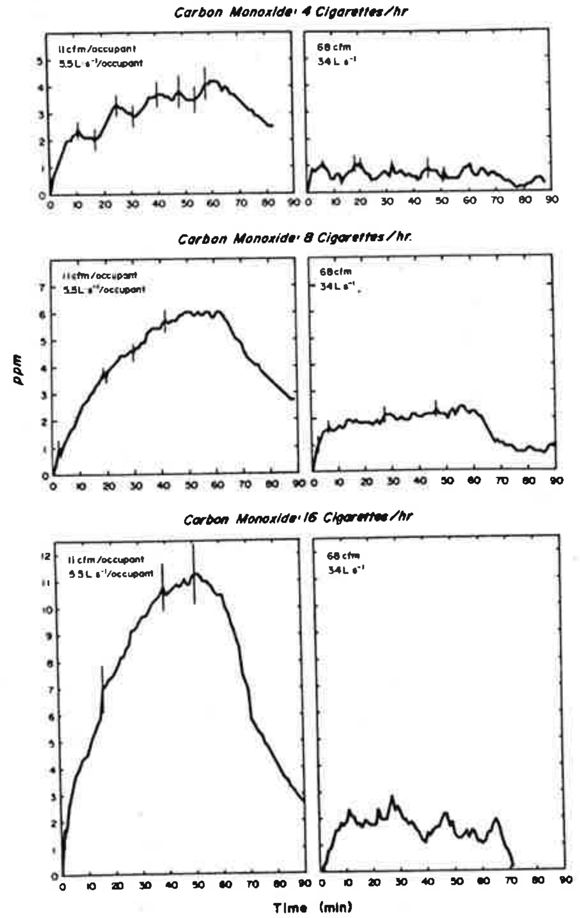

Fig. 9. Variation of carbon monoxide during smoking (t = 0 to 60 min) and postsmoking segments for the lowest and highest ventilation rates, 11 and 68 cfm (5.5 and 34 $L sec^{-1}$) per occupant, respectively. The bars depict standard errors. The number of replicate sessions ranged from 5 to 11, with the exception of the condition 68 cfm (34 $L sec^{-1}$) per occupant at 16 cigarettes/h, which includes measurements from only one session. (ppm = μL/L.)

tion followed a pattern much like that of carbon monoxide: (1) cyclicity at 4 cigarettes per hour (Fig. 10), and (2) a time-average rise throughout the smoking segment at ventilation rates less than 25 cfm (12.5 $L sec^{-1}$) per occupant for all three rates of smoking. TSP differed from CO in the relative severity of the levels achieved. Unlike the graphs for CO, the graphs for TSP include the presmoking baseline, typically less than 35 $\mu g/m^3$.

CO and TSP in steady-state conditions

A total of 51 size distribution measurements were taken. The volume distribution was log-normally distributed with a volume median diameter of 0.225 μm and a geometric standard deviation of 2.08. Approximately 98% of the volume fell between 0.05 and 1.0 μm. The aerosol size distributions did not vary significantly with relative humidity. Previous investigators using various aerosol measurement techniques have reported median diameters ranging from 0.1 to 1.0 μm with the controlling factor being dilution (Hinds, 1978).

Equilibrium concentrations of CO and TSP for various smoking and ventilation rates under virtually ideal mixing are shown in Figs. 11 and 12. Also indicated are relevant ambient air quality standards. The national ambient air quality standard for CO of 35 ppm ($\mu L/L$) averaged over 1 h was never reached during the experiments and the standard of 9 ppm ($\mu L/L$) averaged over 8 h was exceeded only for conditions of low ventilation rate and high smoking rate. A ventilation rate of approximately 20 cfm (10 $L sec^{-1}$) per occupant or greater would apparently suffice to control CO levels in this well-mixed chamber, except during the extreme smoking rate of 24 cigarettes per hour.

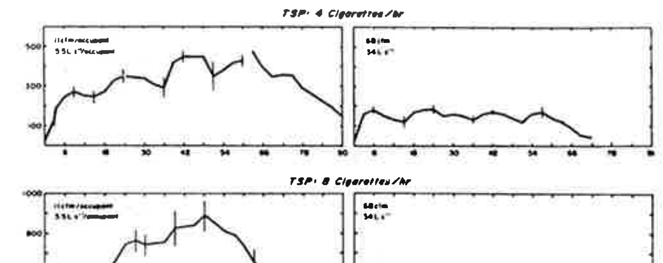

Fig. 10. Variation of total suspended particulate (TSP) mass concentration during smoking (t = 0 to 60 min) and postsmoking segments for the lowest and highest ventilation rates, 11 and 68 cfm (5.5 and 34 $L sec^{-1}$) per occupant, respectively. The bars depict standard errors where the number of replicate sessions exceeded two. The average number of sessions equalled seven. Note that the ordinate for 16 cigarettes/h differs by a factor of 2 from the ordinates for 4 and 8 cigarettes/h.

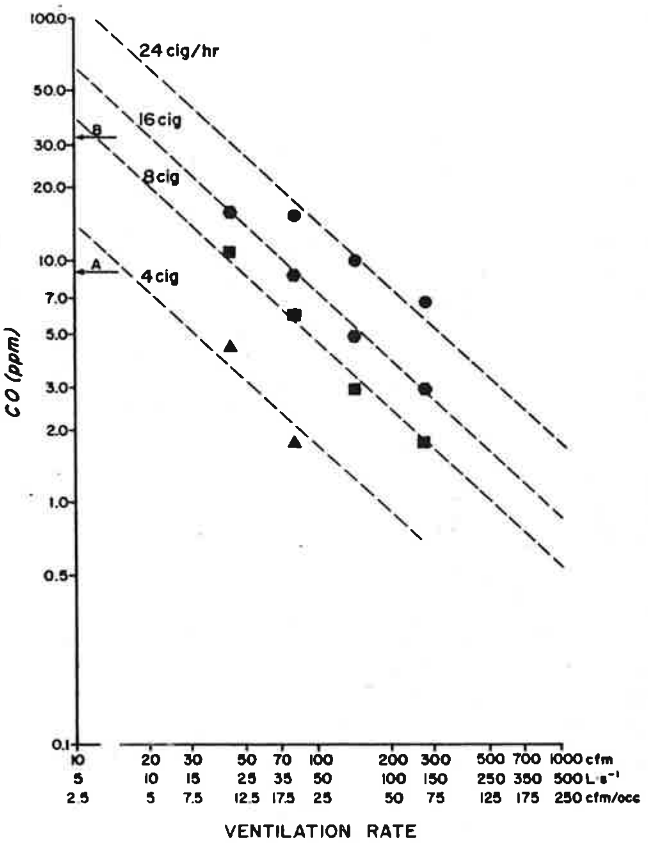

Fig. 11. Function showing how carbon monoxide varied with ventilation rate at various rates of smoking. The data represent steady-state levels attained when smoking a single brand of cigarette (17 mg "tar," FTC method). The level designated *A* represents the national ambient air quality standard of 9 ppm (8-h running average). The level designated *B* represents the national ambient air quality standard of 35 ppm (1-h average). (ppm = $\mu L/L$.)

Steady-state concentrations of TSP revealed that the national ambient primary and secondary air quality standards (75 and 60 $\mu g/m^3$) designed to protect public health and welfare would be exceeded readily even under conditions of low smoking (4 cigarettes/h) and high ventilation (68 cfm or 34 $L sec^{-1}$) per person (Fig. 12). Various combinations would also produce TSP concentrations in excess of less stringent ambient standards, such as that for an air pollution emergency.

Concentrations of condensation nuclei measured over the same conditions as those shown in Figs. 11 and 12 never exceeded 105,000/cm^3. For sake of comparison, we noted that atmospheric levels of condensation nuclei for New York for a winter period averaged 105,000/cm^3 (Leaderer *et al.*, 1981). The low levels seen in the experiments were presumably due to the rapid growth of the aerosol by coagulation.

Our experiment allows an examination of the effectiveness of removal of contaminants under conditions where there is no active cleaning of the recirculated air.

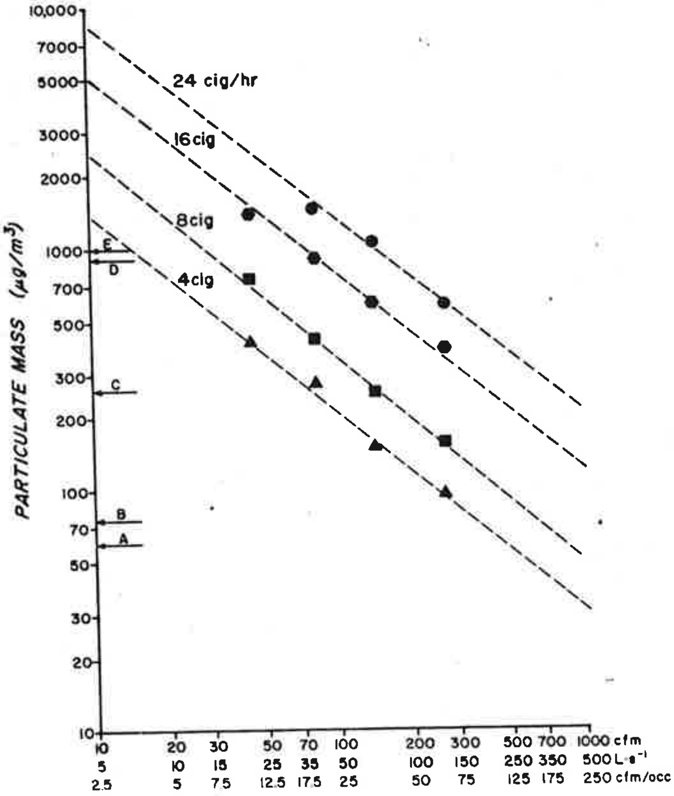

Fig. 12. Function showing how particulate mass concentration varied with ventilation rate at various rates of smoking. The data represent steady-state levels attained when smoking a single brand of cigarette. Level *A*: secondary ambient air quality standard (annual arithmetic average) set to protect public welfare; level *B*: primary ambient air quality standard set to protect public health; level *C*: the 24-h average level set to protect public health and not to be exceeded more than once a year; level *D*: the 24-h average concentration for air pollution emergency; level *E*: the 24-h average concentration for significant harm.

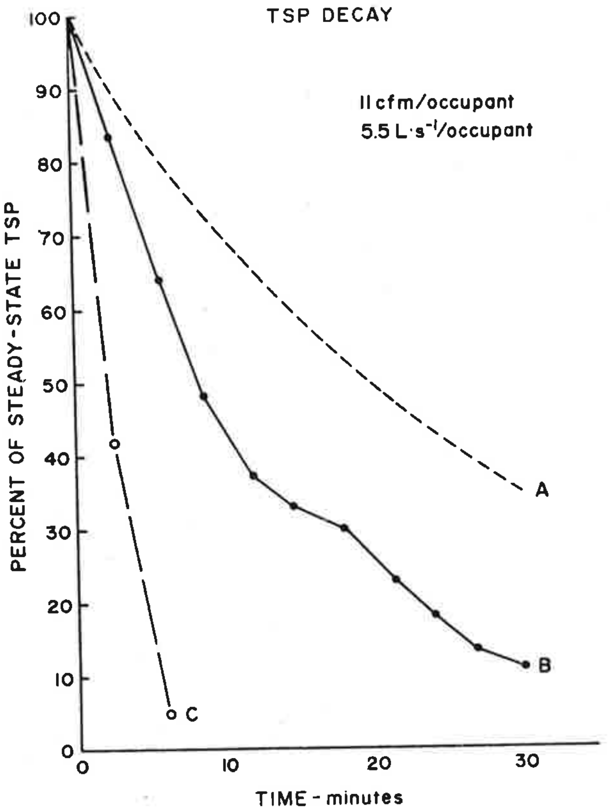

Fig. 13. The decay of TSP and after steady-state levels had been reached and smoking was terminated. Ventilation rate was 44 cfm (22 L sec^{-1}) or 2.2 ach and the smoking rate was 8 cigarettes/h. Curve *A* indicates the decay if only ventilation rate were responsible for TSP removal; curve *B* shows the actual decay measured; curve *C* shows the decay when the recirculated air was passed through a electrostatic precipitator. Decays are presented as percent of steady-state concentration.

And, by passing the recirculated air through the electrostatic air cleaner, we could evaluate the efficiency of this air cleaning device for removal of TSP.

Figure 13 depicts typical decay curves of TSP from steady-state levels upon cessation of smoking, for the measured removal rate (curve *B*) and for ventilation and air cleaning with an electrostatic precipitator (curve *C*). Also presented is the percent decay expected if ventilation alone were entirely responsible for the removal of TSP (curve *A*). Concentration decayed exponentially as anticipated; nevertheless, the measured removal rate (curve *B*) without the precipitator was far greater than could be accounted for by ventilation alone. According to our calculations from the mass balance equation, ventilation accounted for little more than one-half of the total decay. Removal by surfaces presumably accounted for the rest. TSP decay obtained when the recirculated air was diverted through the electrostatic precipitator upon cessation of smoking (curve *C*) indicates the high effectiveness of such a device.

Figures 14 and 15 depict measured effective ventila-

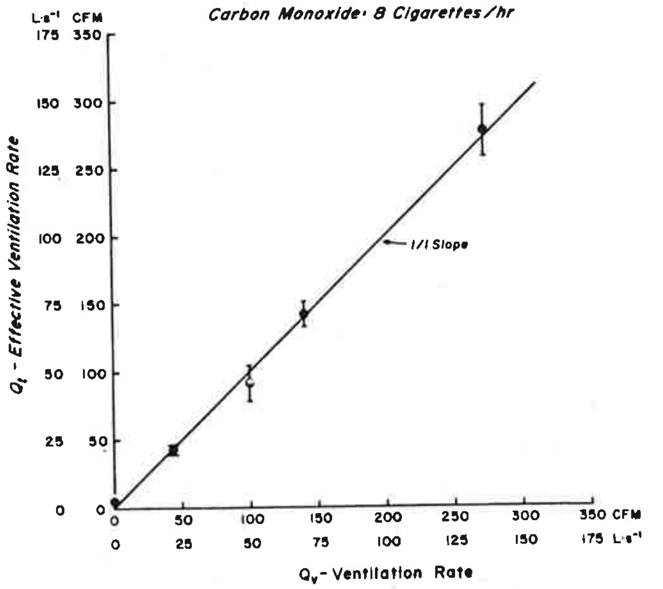

Fig. 14. Means and standard errors of effective ventilation rate (Q_t), calculated from the decay of carbon monoxide, versus nominal ventilation rate (Q_v) for carbon monoxide. The data points were calculated from the best fit regression lines of decay curves for experiments conducted at a smoking rate of 8 cigarettes/h.

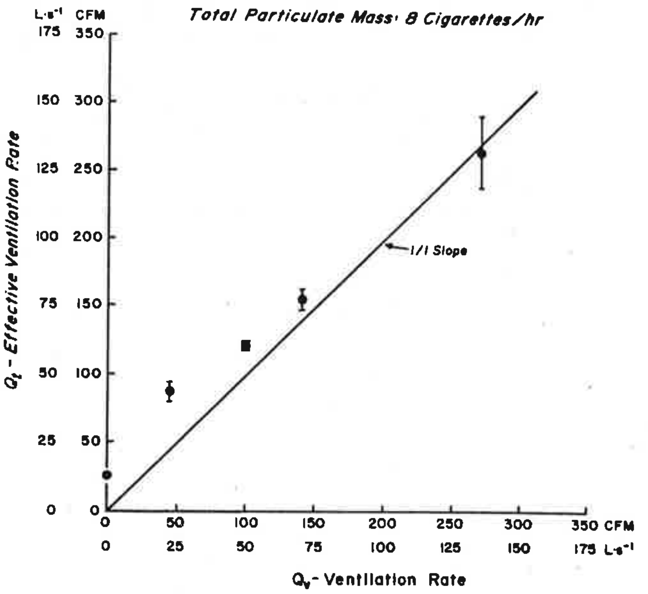

Fig. 15. Means and standard errors of effective ventilation rate (Q_t) for total suspended particulate mass calculated from the best-fit regression lines of decay curves for experiments conducted at smoking rates of 8 cigarettes/h. Calculated rate is plotted against nominal ventilation rate (Q_v). The 1/1 slope line is shown.

tion rate (measured removal rate) versus nominal ventilation rate (ventilation rate set in chamber) under conditions of smoking 8 cigarettes/h (one cigarette always being smoked). For CO, ventilation rate appeared to be the only removal mechanism. For TSP, however, the effective ventilation rate exceeded all but the highest nominal rates. Surfaces in an enclosed room, therefore, seem to be important sinks for tobacco smoke indoors, thus increasing the effective removal rate. The removal rate of TSP will undoubtedly depend upon type of surface, surface to volume ratio, TSP concentration, mixing rate, ventilation rate, and recirculation rate. It is noteworthy that absorbed particles may carry condensed volatiles which could evaporate over time, thereby imparting a lingering odor. High ventilation rates or cleaning of the recirculated air may be necessary to overcome this effect.

Discussion

The investigation of occupancy odor suggested that low ventilation rates will meet surprisingly high acceptance even under crowded conditions of sedentary occupancy. As little as 5 cfm (2.5 Lsec^{-1}) per occupant may be acceptable to three quarters of visitors, though a rate between 5 and 10 cfm (2.5 and 5 Lsec^{-1}) seems a more likely candidate for blanket acceptance. This outcome has much in common with Yaglou's recommendations in cases of moderate to large air space per person, i.e., above 500 ft^3 (14 m^3), but falls much below his recommendations for crowded spaces.

Ventilation requirements for smoking can be based on various indices, e.g., odor perceived by visitors, irritation experienced by nonsmoking occupants, haze (smokiness), or criterion concentrations of contaminants. If we apply the same criterion of acceptance to the odor of tobacco smoke that we applied to the odor of occupancy, i.e., 75%–80% acceptance of the odor by visitors, then we can conclude that probably none of the combinations of smoking rate and ventilation rate would consistently meet the criterion even for a mixed group of smokers and nonsmokers. A ventilation rate as high as 100 cfm (50 L sec^{-1}) per smoking occupant might be necessary to meet the criterion of acceptability in situations where smoking occurs more or less continuously.

Our findings on CO and TSP can give some insight into the effectiveness of existing or proposed ventilation requirements during smoking if the criteria of exposure to CO and TSP in excess of the ambient air quality standards can serve as a guide. It should be remembered, however, that ventilation requirements are commonly based in part on psychophysical criteria. The data in Figs. 11 and 12 can be replotted for rough comparison with real-world conditions, that is, the impact of ventilation on level of CO and TSP when one-third of the population smokes at the rate of 2 cigarettes/h with each cigarette smoked for a period of 7.5 min. The data are shown plotted in Fig. 16 with a best-fit line drawn and extended to the point where the ventilation rate would be adequate to meet the primary ambient standard for TSP (background levels subtracted).

The 1981 ASHRAE ventilation standard (ASHRAE, 1981) recommends a modal value of 35 cfm (17.5 Lsec^{-1}) per occupant in smoking areas. It is clear from Fig. 16 that the ASHRAE recommendation will result in TSP exposures close to those specified in the ambient air quality standard if background levels are assumed to be zero. Figures 11, 12, and 16 assume a zero background concentration of CO and TSP, which is never the case. With background concentration of CO and TSP in the outside air, then the ventilation requirements would be higher.

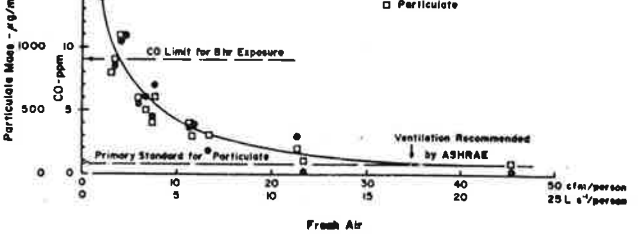

Fig. 16. Data for CO and TSP replotted from Figs. 11 and 12 in order to indicate levels of CO and TSP that would result under various ventilation rates when real-world smoking conditions were approximated; that is, where ⅓ of the population smoked at the rate of 2 cigarettes/h with a smoking time of 7.5 min/cigarette. The recommended ASHRAE standard for ventilation in smoking areas is indicated. (ppm = μL/L.)

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