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# VENTILATION REQUIREMENTS IN BUILDINGS—I. CONTROL OF OCCUPANCY ODOR AND TOBACCO SMOKE ODOR

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**Abstract**—Psychophysical measurements of odor, supplemented with certain physical measurements, were taken to examine ventilation requirements during smoking and nonsmoking occupancy in an environmental chamber. The facility provided the means to compare impressions of visitors (persons who inhaled air from the chamber only briefly) with impressions of occupants. For nonsmoking occupancy, 47 combinations of temperature, humidity, ventilation rate and occupancy density were examined. Odor level depended entirely on ventilation rate per person irrespective of the number of persons in the chamber. The ventilation necessary to satisfy 75 % of visitors equalled only about 4 $\ell\,s^{-1}$ per person. Occupants, however, were satisfied with far less. In an array of 38 conditions of smoking occupancy, the ventilation deemed necessary to satisfy 75 % of visitors under customary conditions of occupancy equalled 17.5 $\ell\,s^{-1}$ per person. For both smoking and nonsmoking conditions, a combination of high temperature (25.5 °C) and humidity (r.h. > 70 %) exacerbated the odor problem. During smoking, carbon monoxide rarely reached dangerous levels, but suspended particulate matter often reached levels considered unacceptable outdoors. The results highlight the energy penalty incurred in ventilation for smoking occupancy.

Index key words: Buildings, carbon monoxide, odor, particulate matter, tobacco smoke, ventilation.

## INTRODUCTION

An analysis of the air in a building will characteristically reveal a large number of organic substances, many at concentrations too low to have any discernible adverse impact. The only sign of their presence may occur via the sense of smell. In the 1930s, there arose the notion that odor level perceived by visitors to an occupied space could offer a quantitative criterion for ventilation requirements in buildings. Various researchers, but principally Yaglou *et al.* (1936), applied psychophysical scaling to the question of how the level of occupancy odor depended on ventilation in a model environment during nonsmoking occupancy. Although various factors, e.g. personal hygiene, had some influence on odor, the most important factor was the relationship between odor level and density of occupancy. In order to hold odor at a moderate level (2 on a scale of 0–4), 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 experimental chamber increased from 3 to 7, the required amount of fresh air per person increased from 3.5 $\ell\,s^{-1}$ to 8 $\ell\,s^{-1}$. For 14 occupants, the required amount of fresh air equalled 12.5 $\ell\,s^{-1}$ per person.

It seemed strange that ventilation requirements should have failed to vary proportionally with density of occupancy, an outcome that would have allowed the rate per person to remain constant with changes in density. Yaglou and Witheridge (1937) recognized the anomaly and even questioned the generality of the previous results. Nevertheless, both American and European standards have relied implicitly or explicitly on Yaglou's estimates, in part because no competing data have emerged (Cain, 1979). In the 1970s, some persons began to question whether the estimates fall above the necessary requirements (Ambrose, 1975). If so, then ventilation for conditions of nonsmoking occupancy might waste considerable energy. The present experiments, which took place in a model environment with an ideal ventilation system, allowed consideration of this matter.

Occupancy odor typifies the less severe end of a continuum of indoor odorous contaminants. Cigarette smoke odor typifies the more severe end. About one-third of the adults in the United States smoke cigarettes and an average smoker consumes about two cigarettes $h^{-1}$. A cigarette emits thousands of chemical constituents in the gas and liquid (aerosol) phases. The aerosol adsorbs readily to surfaces and can discharge volatile constituents long after smokers have left a room. The strong and often lingering odor of cigarette smoke has made it particularly troublesome. Despite its prevalence and severity as a nuisance, quantitative ventilation requirements for tobacco smoke odor have received little attention in the laboratory. In one notable but small study, Yaglou (1955) concluded that 20 $\ell\,s^{-1}$ per smoker would suffice. Others have concluded that higher rates are necessary (Kerka and Humphreys, 1956). The present investigation, larger in scope than any previous investigations, aimed in part to rectify the lack of definitive information regarding how both odor and notable contaminants from cigarettes (e.g. suspended particulate matter) will alter indoor air quality.

## OCCUPANCY ODOR

### *Method*

*Facilities.* Figure 1 presents a schematic of the environmental chamber. The box on the right displays the range of operating conditions. All ductwork and internal surfaces were aluminum. The entire floor (11 m²) served as a diffuser. Air entered via a plenum beneath the floor and streamed upward through 13,900 perforations. The arrangement allowed a volume flow of up to 1000 ℓ s⁻¹ with low linear velocity. Such conditions led to very rapid mixing. A variable percentage of the 1000 ℓ s⁻¹ could comprise fresh, ventilation air.

Another feature of the chamber was a sniffing station. Air from the chamber passed through the station, an aluminum box of 0.11 m³, and eventually went back into a return duct. The box enabled persons to judge the air in the chamber without the need to enter it.

Calibration of ventilation rate, which took place during unoccupied periods, employed carbon dioxide monitored by a Beckman LB-2 Infrared Analyzer. Rate of decay of a known amount of $CO_2$, typically 1 %, indicated ventilation rate.

*Subjects.* One hundred and sixty-five persons participated.

*Procedure.* Main factors included three levels of occupancy (4, 8 and 12 persons), four ventilation rates (2.5, 5, 7.5 and 10 ℓ s⁻¹ per occupant) and four environmental conditions (20 °C r.h. ≤ 50 %, denoted moderate humidity; 23 °C, moderate humidity; 25.5 °C, moderate humidity; and 25.5 °C, r.h. ≥ 70 %, denoted high humidity). Forty-seven combinations of these factors received attention. A session began with psychophysical scaling of a reference odorant. Each participant judged eight concentrations of the woody-pungent alcohol 1-butanol by means of the psychophysical scaling method known as magnitude estimation (Cain and Moskowitz, 1974). The various concentrations (16 to 2048 ppm in 2 : 1 steps) emanated from the eight nozzles (ports) of a Dravnieks binary-dilution olfactometer described in ASTM Standard E-544. The numerical scaling served both to familiarize the participant with the range of available intensities from the olfactometer and to allow the participant to erect an internal numerical scale for use during the main part of the session.

After the participants had completed their numerical judgments of butanol, some persons (denoted occupants) entered the environmental chamber and others (denoted visitors) remained in a waiting room.

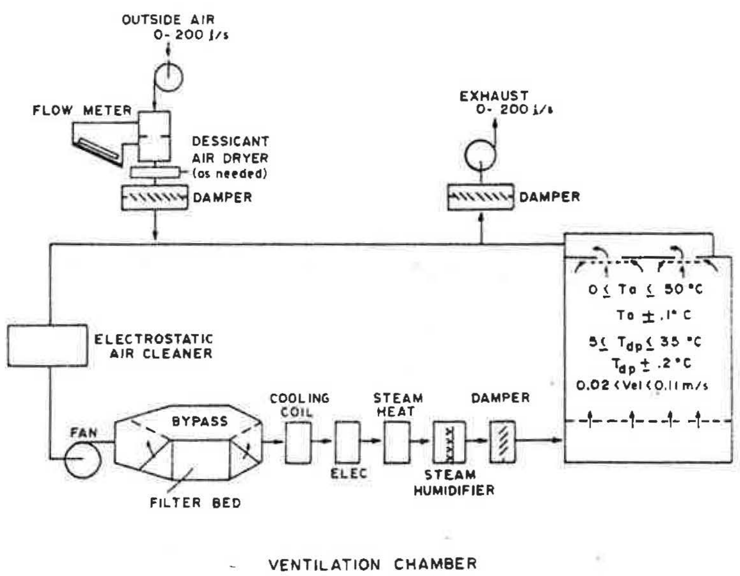


Fig. 1. Schematic view of environmental chamber (shown in cross-section at right) and control equipment. Outside air entered via blower at upper left and exhaust air exited via blower at upper right. Arrows in the cross-section of the chamber depict the flow of air from floor to ceiling. Other information contained in the cross-section include the range and degree of control of ambient dry-bulb temperature ($T_a$) and dew-point temperature ($T_{dp}$) and the range of linear velocity of the air movement (Vel).



Shortly thereafter, the visitors in the waiting room began, one-by-one, to judge the odor at the sniffing station. The trip to the sniffing station required about a 25-m walk through a generally unoccupied and odorless corridor.

After sniffing the air at the station, the visitor assigned the occupancy odor a magnitude estimate from the scale previously generated from judgments of butanol. This manoeuvre served to capture the immediate impression. The person then moved a couple of paces to the location of the olfactometer and sought to find a port, i.e. a concentration of butanol, that equalled (i.e. matched) the intensity of the occupancy odor. Port number, hereafter termed butanol level, served as the primary index of intensity.

The visitor returned to the waiting room after a judgment and told the next person in line to proceed to the station. Normally six to eight visitors participated in a session. We obtained judgments from about 25 visitors for each of the 47 combinations of factors.

At the time of the final match of a 1-h session, the visitor added two other components to the previous estimates of intensity. One component involved marking a 13.5-cm line where the left end equalled no odor and the right end a very strong odor. The other component involved circling one of two choices: acceptable or not acceptable. These referred to the odor experienced only during the final trial of a session. Occupants inside the chamber also made judgments during the final moments of occupancy. These judgments, like those of the visitors, entailed marking 13.5-cm lines for degree of odor and circling the choices acceptable or not acceptable.

### *Results*

Figure 2 shows how odor varied during 47 combinations of density, ventilation rate and environmental conditions. The data points represent medians of the levels (port numbers on left ordinate; ppm on right ordinate) of butanol matched to occupancy odor. The data points arose from judgments made by an average of 26 persons within a given 15-min interval. The standard error of measurement typically fell between one-quarter and one-third of a step on the butanol scale.

Two features stand out: (1) odor spanned only about two port numbers from the most to the least severe conditions and (2) the position and shape of individual functions display considerable fluctuation within the two-unit span. The fluctuations must derive in part from moment-to-moment and session-to-session variations in the stimulus for odor. Although the nominal stimulus, i.e. the number of persons in the chamber, was easy to specify, the actual olfactory stimulus undoubtedly varied with the occupants' diet, personal hygiene, amount of clothing, etc. Some fluctuation could also have arisen from some background odor in the chamber (e.g. occasional odor in the incoming air). Early attempts to quantify any such background odor were discontinued when the results indicated only a barely measurable level.

Fluctuations become less of a burden when the data are averaged in such a way as to focus on the specific questions, "How does odor vary with the number of persons in the chamber?" and "How does odor vary with environmental conditions?" Figure 3(a) depicts butanol matching functions averaged across all four environmental conditions for each density of occupancy. The outcome, unlike that of Yaglou and colleagues, implied no consistent effect of density.

Whereas Fig. 3(a) depicts results taken across environmental conditions and thereby focuses on density, Fig. 3(b) depicts results taken across number of occupants and thereby focuses on the influence of environmental conditions. Only one systematic trend stands out, namely the tendency for the combination of high temperature and high humidity to generate a more intense odor than conditions of moderate humidity. The average influence of high humidity amounted to 0.6 scale units which translates into an increment of 50 % in matched concentration of butanol.

Since density had no apparent effect, Fig. 4 presents composite functions taken across all three densities and across only the three environmental conditions of moderate humidity. The upper panel depicts port numbers, the middle panel ppm (linear coordinates) and the lower panel magnitude estimations, included to show general agreement between this index and butanol matching. These sets of functions offer the most stable estimates of how odor varies with time. The functions in the three panels seem close to steady state at 60 min. In order to find meaning in the levels achieved, we can refer to the relation between acceptability and odor. The function in Fig. 5 arose from the final judgments made in a session. The relation reveals that visitors deemed even the lowest level (butanol level 1) only 85 % acceptable. The visitors found levels 2 and 3 acceptable 80 % of the time. Above level 3, acceptability declined almost linearly.

An absence of clear level dependency between levels 1 and 3 suggests that this portion of the acceptance function may reflect merely "noise-level" dissatisfaction that would occur if odor level ever exceeded threshold. Butanol matching functions obtained with ventilation rates of 2.5 and 5 ℓ s⁻¹ per occupant, however, exceeded level 3 and therefore seem to reflect more than just "noise-level" or baseline dissatisfaction. According to the acceptance function, the odor levels achieved with 2.5 and 5 ℓ s⁻¹ per occupant would fall at about 70 and 78 %, respectively, whereas the odor levels achieved with 7.5 and 10 ℓ s⁻¹ would fall at 80 %.

Table 1 offers a view of how odor acceptability varied across conditions for the particular judges in each condition. Entries on the left refer to odor intensity assessed by the line-marking procedure. This scale allows a direct comparison of how odor level seemed both to visitors and to occupants in the final moments of occupancy. Not unexpectedly, visitors

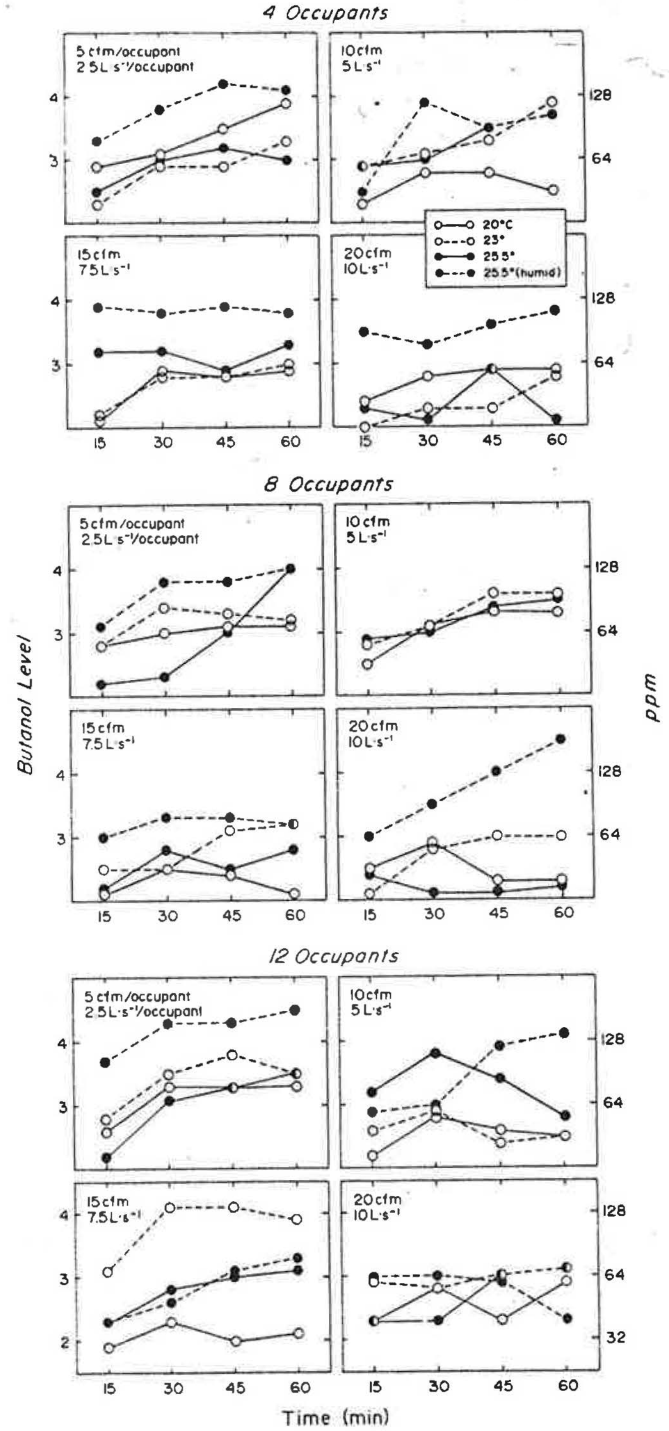


Fig. 2. Butanol matching functions obtained during 47 conditions of occupancy. Each panel shows ventilation (outdoor air) rate per occupant. Left ordinate shows port number of olfactometer; right ordinate shows ppm (v/v in air) of butanol. For reference, 1 ppm equals 3 mg m$^{-3}$.

found the environment more odorous than occupants. Nevertheless, the occupants still judged the high humidity condition much more intense than the moderate humidity conditions, as did the visitors. Percentage acceptance among visitors seemed to track intensity reasonably well and generally confirmed the results for intensity and acceptability shown in Figs 4 and 5.

The correlation between percent acceptance and intensity assessed by line marking equalled −0.87 for



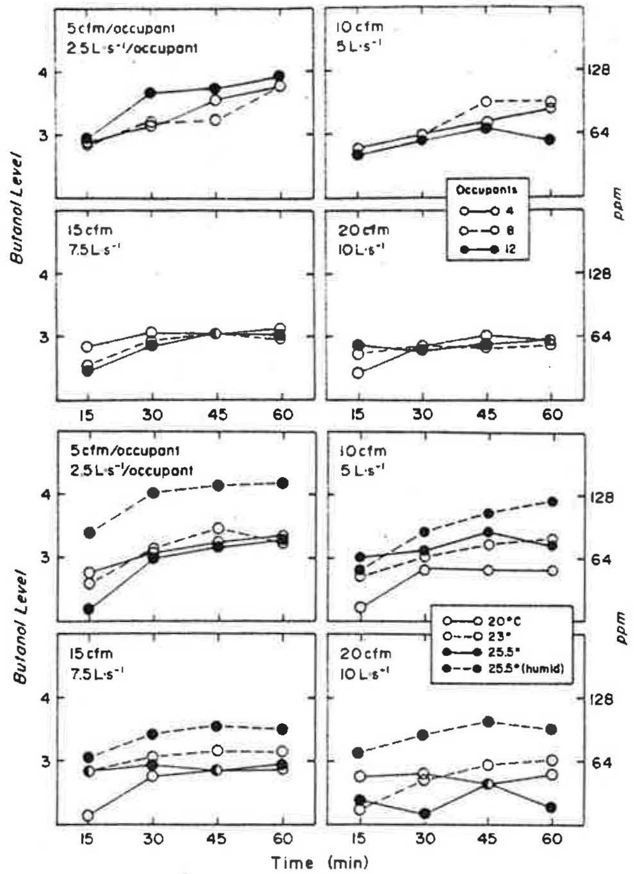


Fig. 3. Top: Butanol matching functions taken across environmental conditions in order to explore whether odor level varied systematically with number of occupants at various ventilation rates ranging from 2.5 ℓ s$^{-1}$ to 10 ℓ s$^{-1}$ per occupant. Bottom: Butanol matching functions taken across number of occupants in order to explore whether odor level varied systematically with environmental conditions.

visitors and −0.74 for occupants. The strengths of these correlations imply that occupant as well as visitor managed to discern and convey considerable information about the odor environment (see Fig. 12).

*Discussion*

This investigation suggests that low ventilation rates will meet reasonably high acceptance, even under crowded conditions of sedentary occupancy. A rate between 2.5 and 5 ℓ s$^{-1}$ per occupant seems likely to satisfy about three quarters of visitors irrespective of occupancy density. But, a rate of 7.5 ℓ s$^{-1}$ per occupant seems necessary to assure 80% acceptance.

The recently issued standard entitled *Ventilation for Acceptable Indoor Air Quality*, ASHRAE 62-1981, of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers implies that indoor air should be unobjectionable to 80% or more of a panel of at least 20 untrained observers (visitors). In view of our finding that only 85% of visitors deemed the very weak butanol level of 1 acceptable, the 80% rule seems rather stringent. Furthermore, rather large percentage changes in ventilation (e.g. from 5 to 7.5 ℓ s$^{-1}$ per occupant) may change acceptance by merely a few percentage points. Accordingly, a small error in estimated acceptance could have large consequences for ventilation requirements.

Whereas previous editions of the ASHRAE standard recommended an increase in ventilation rates per occupant with increasing density of occupancy, the present edition does not. In this respect, the standard and the present results agree. Nevertheless, the standard generally recommends rates below 5 ℓ s$^{-1}$ per occupant, most commonly 3.5 ℓ s$^{-1}$. Whether such rates actually satisfy at least 80% of occupants under field conditions remains a matter of uncertainty. The ASHRAE standard is derived by a process of consensus that includes consideration of existing data and the field experience of professional engineers. Until the present investigation, there has existed no data on the relation between odor intensity and percentage acceptance. Hence, any relation between prescriptive rates,

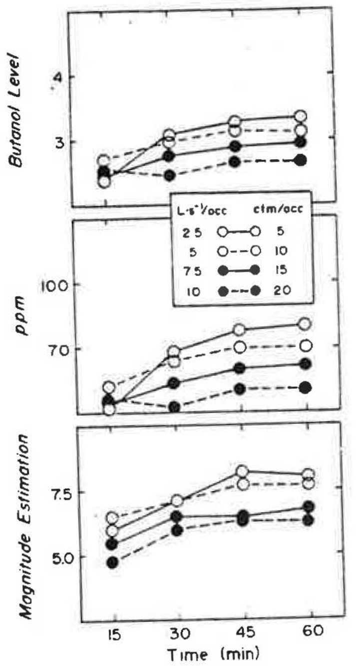


Fig. 4. Top and middle panels depict (on logarithmic and linear ordinates, respectively) butanol matching functions taken across number of occupants and across temperatures, but excluding the humid condition at 25.5 °C. Bottom panel depicts corresponding magnitude estimations.

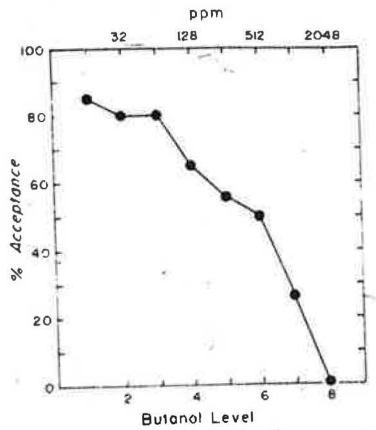


Fig. 5. Showing how acceptance of occupancy odor to visitors varied with equivalent (i.e. matched) level of butanol. The judgments were accumulated across all conditions. As the functions in Fig. 2 imply, the bulk of the intensity judgments fell between butanol levels 2 and 5. Nevertheless, most conditions elicited some individual judgments outside this range. The total number of judgments equalled 902.

Table 1. Perceived intensity (indicated via line-marking) and acceptability obtained from both visitors and occupants during the final moments of the 1-h periods of occupancy

| | r.h. | Odor intensity scale (cm) Visitors | Odor intensity scale (cm) Occupants | % Acceptance Visitors | % Acceptance Occupants |
|---|---|---|---|---|---|
| Four occupants | | | | | |
| $2.5\ \ell\ s^{-1}$* | Moderate | 3.6 | 3.3 | 76 | 95 |
| | High | 5.8 | 5.2 | 39 | 75 |
| $5\ \ell\ s^{-1}$ | Moderate | 3.8 | 1.8 | 81 | 100 |
| | High | 3.7 | 4.2 | 76 | 75 |
| $7.5\ \ell\ s^{-1}$ | Moderate | 3.7 | 3.3 | 77 | 94 |
| | High | 4.9 | 4.9 | 61 | 75 |
| $10\ \ell\ s^{-1}$ | Moderate | 3.2 | 3.5 | 77 | 100 |
| | High | 4.7 | 3.2 | 67 | 100 |
| Eight occupants | | | | | |
| $2.5\ \ell\ s^{-1}$ | Moderate | 4.0 | 2.8 | 70 | 100 |
| | High | 6.6 | 5.3 | 48 | 87 |
| $5\ \ell\ s^{-1}$ | Moderate | 5.2 | 2.7 | 61 | 92 |
| $7.5\ \ell\ s^{-1}$ | Moderate | 3.7 | 3.3 | 83 | 91 |
| | High | 5.3 | 3.9 | 62 | 88 |
| $10\ \ell\ s^{-1}$ | Moderate | 3.6 | 3.6 | 81 | 91 |
| | High | 4.8 | 3.8 | 74 | 92 |
| Twelve occupants | | | | | |
| $2.5\ \ell\ s^{-1}$ | Moderate | 5.7 | 3.4 | 57 | 94 |
| | High | 5.4 | 4.1 | 59 | 88 |
| $5\ \ell\ s^{-1}$ | Moderate | 3.3 | 3.0 | 82 | 97 |
| | High | 6.1 | 4.1 | 48 | 74 |
| $7\ \ell\ s^{-1}$ | Moderate | 4.2 | 3.4 | 76 | 90 |
| | High | 4.6 | 3.5 | 80 | 81 |
| $10\ \ell\ s^{-1}$ | Moderate | 4.1 | 3.1 | 84 | 94 |
| | High | 3.8 | 3.2 | 95 | 97 |

* Ventilation rate per occupant ($1\ \ell\ s^{-1}$ = 2 cfm).



such as those in the standard, and any criterion level of acceptance has been vague. It is noteworthy that some air continuously enters buildings adventitiously through unseen apertures, doors, etc. (ASHRAE, 1981). Such infiltration increases the actual ventilation rate by a variable, but often considerable, amount. A building with a design ventilation rate of $5\ \ell\ s^{-1}$ per occupant may readily have an actual rate of $7.5\ \ell\ s^{-1}$ per occupant.

In a recent field experiment, Duffee *et al.* (1980), using methodology very similar to that used here, measured an average butanol level of 2.7 in a variety of nonsmoking spaces (classrooms, hospital rooms, nurses station). Visitors assessed acceptability at 75%. This degree of acceptance falls reasonably close to expectations derived from our results and lends encouragement to the conclusion that acceptance measured in the context of our chamber may generalize to field situations.

## TOBACCO SMOKE ODOR

### *Method*

*Facilities.* Facilities included the chamber, olfactometers, etc., used in the previous experiment. In order to monitor physical and chemical contaminants during cigarette smoking, a 5-cm diameter PVC tube led about $1.5\ \ell\ s^{-1}$ from inside the chamber to an instrument rack outside. The instruments included a carbon monoxide analyzer (Ecolyzer, Energetics Science, Inc.), a particle mass monitor (Model 3200A, Thermo-Systems, Inc.), and a condensation nuclei monitor (RICH 100, Environment One).

The carbon monoxide analyzer was calibrated before each session. Air sampled by the analyzer was prehumidified. The particle mass monitor employed two piezoelectric quartz crystals as sensors. These were factory calibrated. The instrument measured total mass of particles in the size range 0.01–20 $\mu$m. Its output is reported here as total suspended particulate mass (TSP).

*Subjects.* Ninety-two persons participated.

*Procedure.* Variables of interest included three rates of smoking (4, 8, and 16 cigarettes per hour), six rates of ventilation (5.5, 8, 10, 17.5, and $34\ \ell\ s^{-1}$ per occupant), and the four environmental conditions of the previous experiment. Thirty-eight combinations were studied. Each led to a function that described how odor varied over a period that began with 15-min of nonsmoking

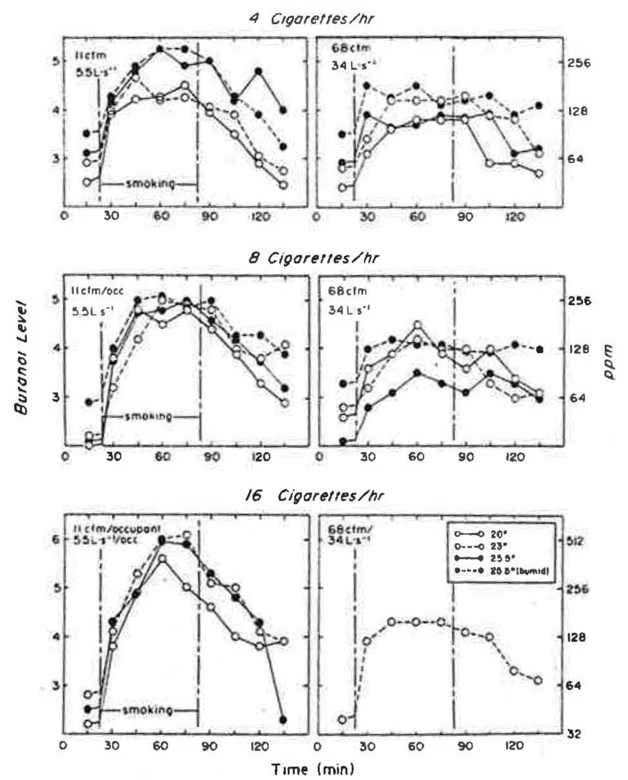


Fig. 6. Butanol matching functions obtained during the lowest and highest ventilation rates, (5.5 and $34\ \ell\ s^{-1}$) per occupant, respectively. Butanol level (port number of olfactometer) is shown on left ordinate and ppm (v/v in air) is shown on right ordinate. Smoking began in the interval between 15 and 20 min and ended in the interval between 75 and 90 min.

occupancy (pre-smoking segment), then continued with 60-min of smoking, and ended with 60-min of nonsmoking occupancy (post-smoking segment) for a total of 135 min. Erection of a function required judgments from approximately 25 observers over three or four sessions (approximately 6–8 observers per session). Roughly one third of the participants smoked cigarettes regularly. When they served as visitors (i.e. as judges of odor at the sniffing station), smokers had the opportunity to smoke one or two cigarettes in an area apart from the other visitors during a 3-h period of participation.

For purposes of generating emissions, four smokers occupied in the chamber. The composition of the group varied from session to session. During the smoking segment, the occupants smoked serially. A total smoking rate of four cigarettes $h^{-1}$ required each occupant to smoke one cigarette for 7.5 min during one 15-min period. A rate of eight cigarettes $h^{-1}$ required each occupant to smoke two cigarettes. A rate of 16 cigarettes $h^{-1}$ required each occupant to smoke four cigarettes. Only at the 16-cigarette rate did occupants smoke in pairs. Occupants smoked their customary brands. Throughout the investigation, the various occupants smoked more than 30 brands.

Physical measurements of air quality proceeded continuously throughout the periods of presmoking, smoking, and postsmoking occupancy. Background levels were monitored periodically.

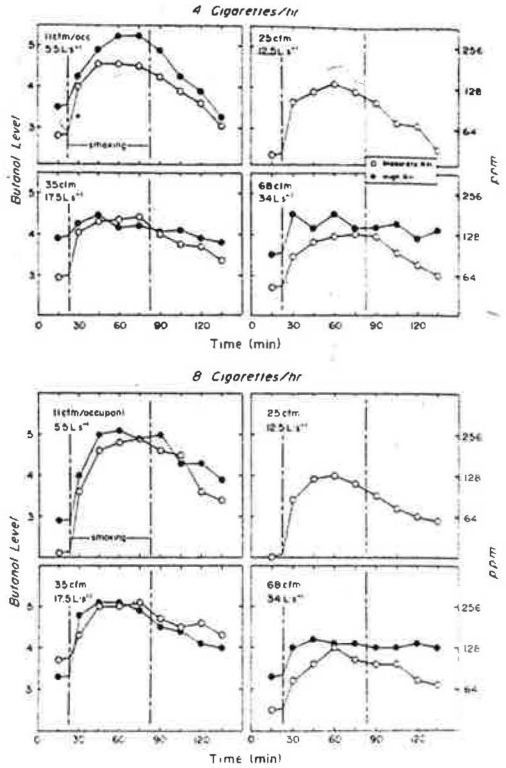


Fig. 7. Butanol matching functions averaged across conditions of moderate r.h. (open circles) and functions obtained at 25.5 °C, high r.h. (closed circles).

*Results*

*Psychophysical measures.* 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 (Fig. 8). The points in the figure represent medians of judgments pooled within 15-min intervals. The matching functions span a substantial portion of the range of butanol levels. Median butanol levels as high as 5 occurred routinely at the lower ventilation rates. Such levels never occurred in the study of occupancy odor. In some instances, high judgments seemed to derive from an elevated baseline. Judgments in the pre-smoking segment were sometimes only poorly related to the ventilation rate. In order to run the hundreds of sessions necessary for thorough exploration of the relevant variables, it sometimes became necessary to use the chamber for successive sessions only 1–2 h apart. Even scrupulous maintenance and heavy ventilation between sessions could not always eliminate lingering odors from adsorbed smoke products under such circumstances. As it turned out, these factors actually posed no difficulties for the interpretation of the psychophysical results.

One systematic effect notable in initial judgments occurred with the combinations of high temperature and high humidity. Figure 7 reveals that the functions for the hot, humid condition (r.h. $\geq 70\%$) began an average of 0.6 butanol scale units above the average for the conditions of moderate humidity (r.h. $\geq 50\%$). This initial difference falls closely in register with that obtained in the study of occupancy odor. By the end of the smoking segment, the difference shrank to 0.15 scale units on the average. Such shrinkage suggested that the influence of temperature and humidity lay in part in the magnitude of occupancy odor produced at the outset. It seems likely that previously adsorbed tobacco smoke causes the bodies and clothing of smokers to emit more odorous material than those of nonsmokers and that such emissions (desorption products) may exhibit temperature and humidity dependence.

Figure 8 displays odor intensity on the butanol matching scale (ppm) normalized to percentages. The figure includes data for moderate humidity only. A scale value of 100% equals the intensity of pre-smoking occupancy odor. The normalization procedure rested on the assumption that the high ventilation rates used to combat cigarette odor would control occupancy odor during the first 15 min with relative ease, a situation that would therefore blunt any dependence of that odor on such high rates of ventilation. Figure 8 also contains, for reference, a function that depicts how magnitude of mere occupancy odor varied over time with a ventilation rate



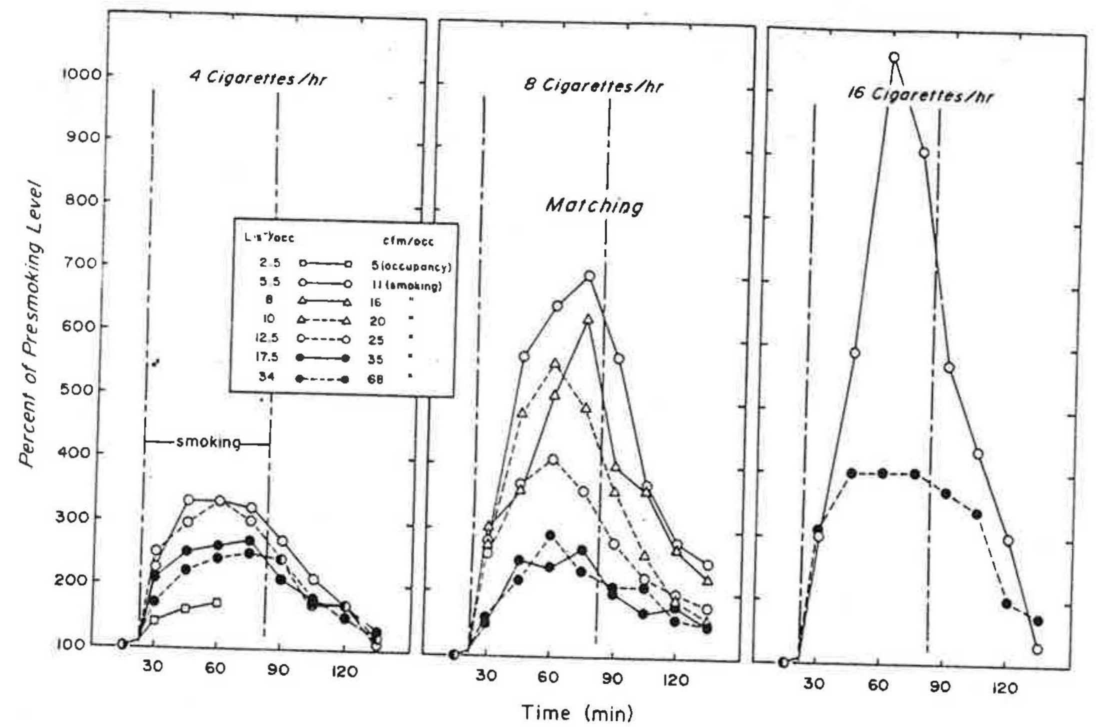


Fig. 8. Butanol matching functions averaged across conditions of moderate humidity and expressed as percentage of odor level (ppm butanol) achieved during 15 min of nonsmoking occupancy. The functions uniformly give the impression that odor level decreased before smoking ceased. This impression arises in part because the data points are connected with straight lines. Nevertheless, in some instances odor did reach a peak and then decline before cessation of smoking. Olfactory adaptation could perhaps account for some such reductions.

of only 2.5 $\ell\,s^{-1}$ per occupant. 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 eight and sixteen cigarettes than at four cigarettes $h^{-1}$. At the low rate of smoking, ventilation rates ranging from 5.5–34 $\ell\,s^{-1}$ per 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 strong dependence on ventilation at rates sufficiently high to prevent significant accumulation of contaminants from cigarette to cigarette. When the occupants smoked only four cigarettes $h^{-1}$, 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. 9, left side) followed a pattern similar to that obtained previously with occupancy odor. In the present case, however, the high odor levels precluded generally high acceptance. Seen on a condition-by-condition basis, as in Table 2, only two combinations of smoking rate and ventilation rate appeared acceptable to as many as 75% of visitors during the period of active smoking. At the smoking rate of four cigarettes and at moderate humidity, approximately two-thirds of visitors found ventilation rates at or above 12.5 $\ell\,s^{-1}$ per occupant acceptable. High humidity led to higher odor intensity and substantially lower acceptability.

Inclusion of both smokers and nonsmokers among the visitors permitted erection of separate acceptance functions for the two groups (Fig. 9, 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 sizable 3 butanol scale units. If the data yielded by the entire group had left any doubt about the need for high ventilation during smoking, that doubt should disappear with consideration of nonsmokers. None of the conditions in the present investigation would satisfy even 2/3 of nonsmokers. Unlike the visitors, however, occupants (smokers themselves) found the odor of the environment generally acceptable during and after smoking (Table 2).

*Physical measures.* Figure 10 shows how carbon monoxide attributable to smoking varied with time for various rates of smoking at the lowest and highest

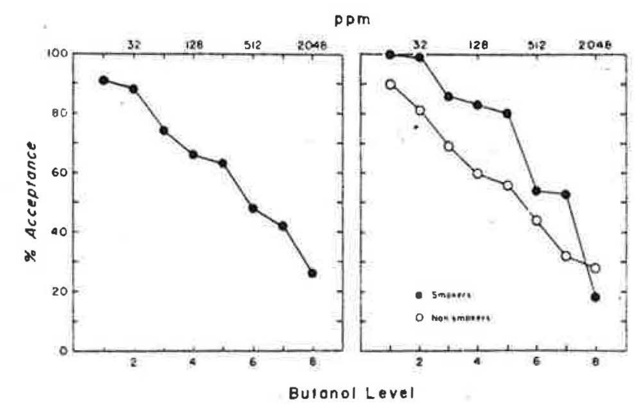


Fig. 9. Left: The relation between acceptance and intensity of tobacco smoke odor, expressed as butanol equivalent. The data comprise the impressions of all visitors in all experiments. Total number of observations equalled 2357. Right: The relation between acceptance and odor intensity for smokers and nonsmokers separately.

ventilation rates. In this and subsequent graphs, $t = 0$ min represents the point when smoking began. The curves for four cigarettes $h^{-1}$ display a cyclicity associated with the regularity of the smoking, i.e. one cigarette every 15 min. During any individual run, the peaks stood out even more clearly than in the average records. Often the peaks in an individual run varied markedly in magnitude, an outcome that reflected differences in emission across cigarettes and across smokers. Standard errors, depicted on the graphs, reveal the session-to-session variability that, in a manner of speaking, confronted the psychophysical observers.

At the smoking rate of four cigarettes $h^{-1}$ and a ventilation rate of 5.5 $\ell\ s^{-1}$ per occupant, the concentration of carbon monoxide grew from cigarette to cigarette. The failure to achieve steady state even during the course of a full hour implies inadequate control of the contaminant, though carbon monoxide in fact failed to reach obviously unhealthy levels during the sessions. The national ambient air quality standard for this pollutant limits its concentration to 9 ppm averaged over an 8-h period and 35 ppm averaged over a 1-h period. At ventilation rates of 12.5 and 17.5 $\ell\ s^{-1}$ per occupant, carbon monoxide levels during smoking of four cigarettes $h^{-1}$ rarely grew more than 3 ppm above background.

At smoking rates of eight and sixteen cigarettes $h^{-1}$, individual cigarettes did not show up as discernible peaks in the average records (Fig. 10). As in the case of four cigarettes $h^{-1}$, the curves continued to climb throughout the period of smoking whenever the ventilation rate fell below 12.5 $\ell\ s^{-1}$. Even rates above 12.5 $\ell\ s^{-1}$ 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 carbon monoxide seemed likely to remain within the limit specified by the national ambient air quality standard even if smoking had continued.

Total suspended particulate (TSP) mass concentration followed a pattern much like that of carbon monoxide: (1) cyclicity at four cigarettes $h^{-1}$ (Fig. 11) and (2) a time-averaged rise throughout the smoking segment at ventilation rates less than 12.5 $\ell\ s^{-1}$ per occupant for all three rates of smoking. Unlike the graphs for carbon monoxide, the graphs for TSP include the presmoking baseline, typically less than 35 $\mu g\ m^{-3}$. TSP differed from carbon monoxide in the relative severity of the levels achieved. In the most severe case, TSP exceeded background by a factor of about 40.

*Discussion*

The relation between percent acceptance and odor intensity assessed by line marking came out much the same in the experiments on smoking as in the experiments on nonsmoking occupancy. Figure 12 depicts the fundamental commonality of the data in both sets of experiments. The correlation coefficient for percent acceptance and intensity approached $-0.9$ for judgments of visitors for each contaminant (i.e. occupancy odor and tobacco smoke odor) separately and for the joint set of data. And, the coefficient equalled about $-0.7$ for the judgments of occupants for each contaminant separately and for the two jointly. Agreement among visitors from one set of experiments to another suggests that visitors decided on acceptability on the basis of odor intensity without regard to quality. It would be of interest to learn whether this simple outcome will generalize to other indoor odorous contaminants, such as cooking odors.

So far, we have specified ventilation rate in terms of $\ell\ s^{-1}$ per occupant. For smoking occupancy, we could also specify ventilation in terms of volume flow per cigarette. In the present investigation, this ranged from



Table 2. Perceived intensity (indicated via line marking) and acceptability obtained from both visitors and occupants during the final moments of the smoking segment and of the post-smoking segment

| | r.h. | Odor intensity scale (cm) Visitors Smoking | Visitors Post-smoking | Occupants Smoking | Occupants Post-smoking | % Acceptance Visitors Smoking | Visitors Post-smoking | Occupants Smoking | Occupants Post-smoking |
|---|---|---|---|---|---|---|---|---|---|
| 4 cigarettes $h^{-1}$ | | | | | | | | | |
| 5.5 $\ell\ s^{-1}$ * | Moderate | 5.1† | 3.8 | 4.2 | 3.1 | 55 | 75 | 97 | 97 |
| | High | 6.6† | 4.8 | 5.9 | 3.6 | 64 | 52 | 75 | 83 |
| 12.5 $\ell\ s^{-1}$ | Moderate | 4.8 | 3.7 | 3.9 | 3.4 | 76 | 85 | 97 | 97 |
| | High | — | — | — | — | — | — | — | — |
| 17.5 $\ell\ s^{-1}$ | Moderate | 4.7 | 3.8 | 3.5 | 3.0 | 66 | 74 | 100 | 100 |
| | High | 5.6 | 4.9 | 5.3 | 4.7 | 43 | 50 | 82 | 83 |
| 34 $\ell\ s^{-1}$ | Moderate | 4.3 | 3.3 | 3.2 | 2.5 | 71 | 87 | 100 | 100 |
| | High | 6.3 | 5.5 | 4.0 | 3.8 | 42 | 50 | 100 | 100 |
| 8 cigarettes $h^{-1}$ | | | | | | | | | |
| 5.5 $\ell\ s^{-1}$ | Moderate | 5.8 | 4.4 | 3.6 | 2.9 | 54 | 78 | 94 | 98 |
| | High | 7.1 | 5.4 | 4.2 | 3.7 | 25 | 52 | 92 | 92 |
| 10 $\ell\ s^{-1}$ | Moderate | 5.9 | 3.9 | 3.4 | 2.0 | 47 | 72 | 100 | 100 |
| | High | — | — | — | — | — | — | — | — |
| 12.5 $\ell\ s^{-1}$ | Moderate | 4.8 | 3.6 | 3.9 | 3.0 | 68 | 91 | 96 | 97 |
| | High | — | — | — | — | — | — | — | — |
| 17.5 $\ell\ s^{-1}$ | Moderate | 5.5 | 4.5 | 4.5 | 3.9 | 51 | 70 | 96 | 93 |
| | High | 6.1 | 4.7 | 4.2 | 4.0 | 39 | 68 | 73 | 75 |
| 34 $\ell\ s^{-1}$ | Moderate | 4.3 | 3.6 | 4.1 | 3.3 | 90 | 92 | 97 | 100 |
| | High | 4.5 | 4.4 | 4.8 | 3.9 | 71 | 71 | 67 | 75 |
| 16 cigarettes $h^{-1}$ | | | | | | | | | |
| 5.5 $\ell\ s^{-1}$ | Moderate | 6.8 | 5.0 | 5.6 | 4.1 | 41 | 73 | 60 | 90 |
| | High | | | | | | | | |
| 34 $\ell\ s^{-1}$ | Moderate | 4.4 | 3.5 | 4.8 | 2.7 | 69 | 81 | 83 | 100 |

* Ventilation rate per occupant (1 $\ell\ s^{-1}$ = 2 cfm).
† Judgments came from at least 21 different persons in conditions of moderate humidity and at least 24 different persons in conditions of high humidity. Average standard error equalled 0.46 for moderate humidity and 0.74 for high humidity.

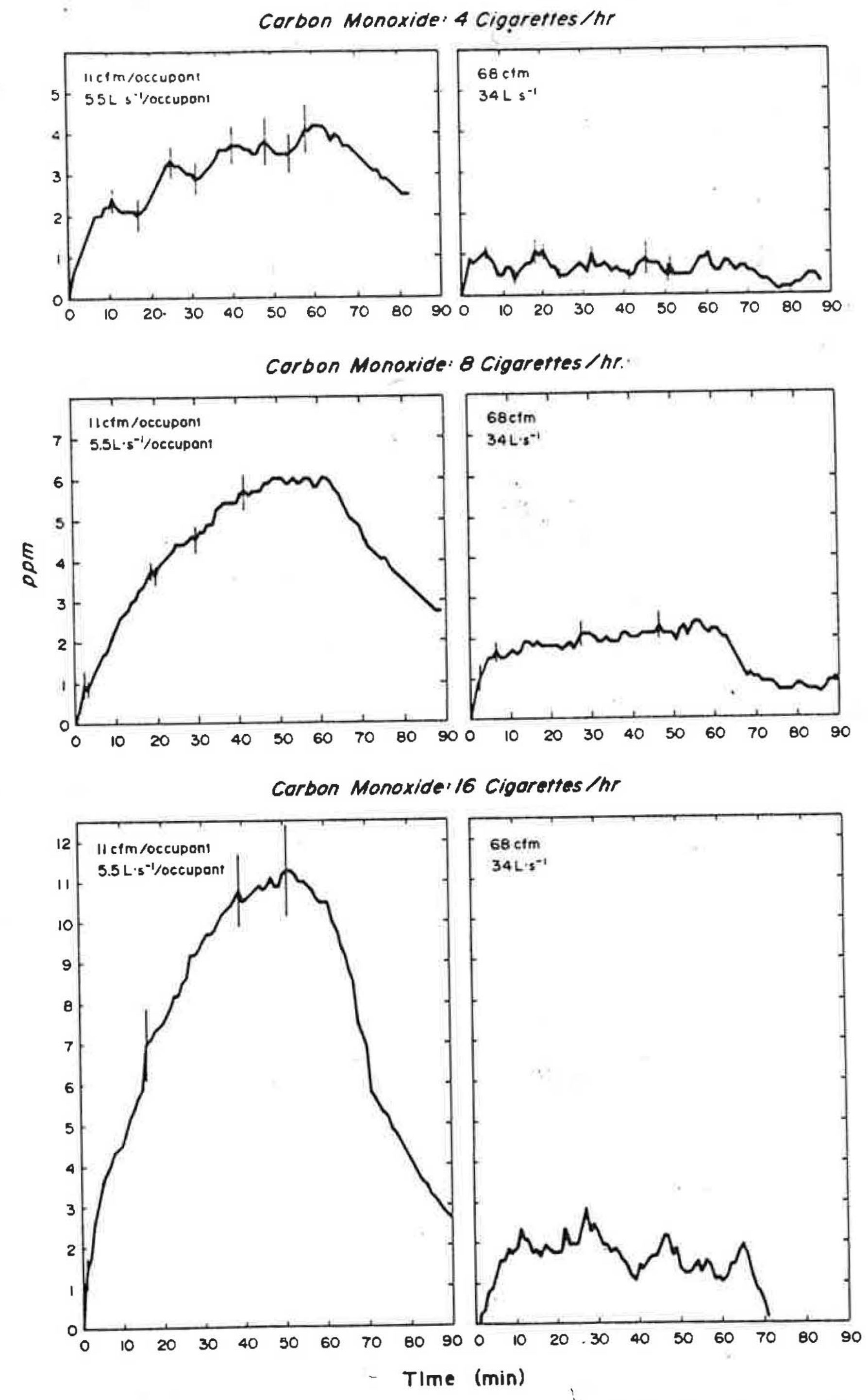


Fig. 10. Variation of carbon monoxide during smoking ($t$ = 0–60 min) and postsmoking segments for the lowest and highest ventilation rates, 5.5 and 34 $\ell$ $s^{-1}$ per occupant. The bars depict standard errors. The number of replicate sessions ranged from 5 to 11, with the exception of the condition 34 $\ell$ $s^{-1}$ per occupant at sixteen cigarettes per hr, which includes measurements from only one session.



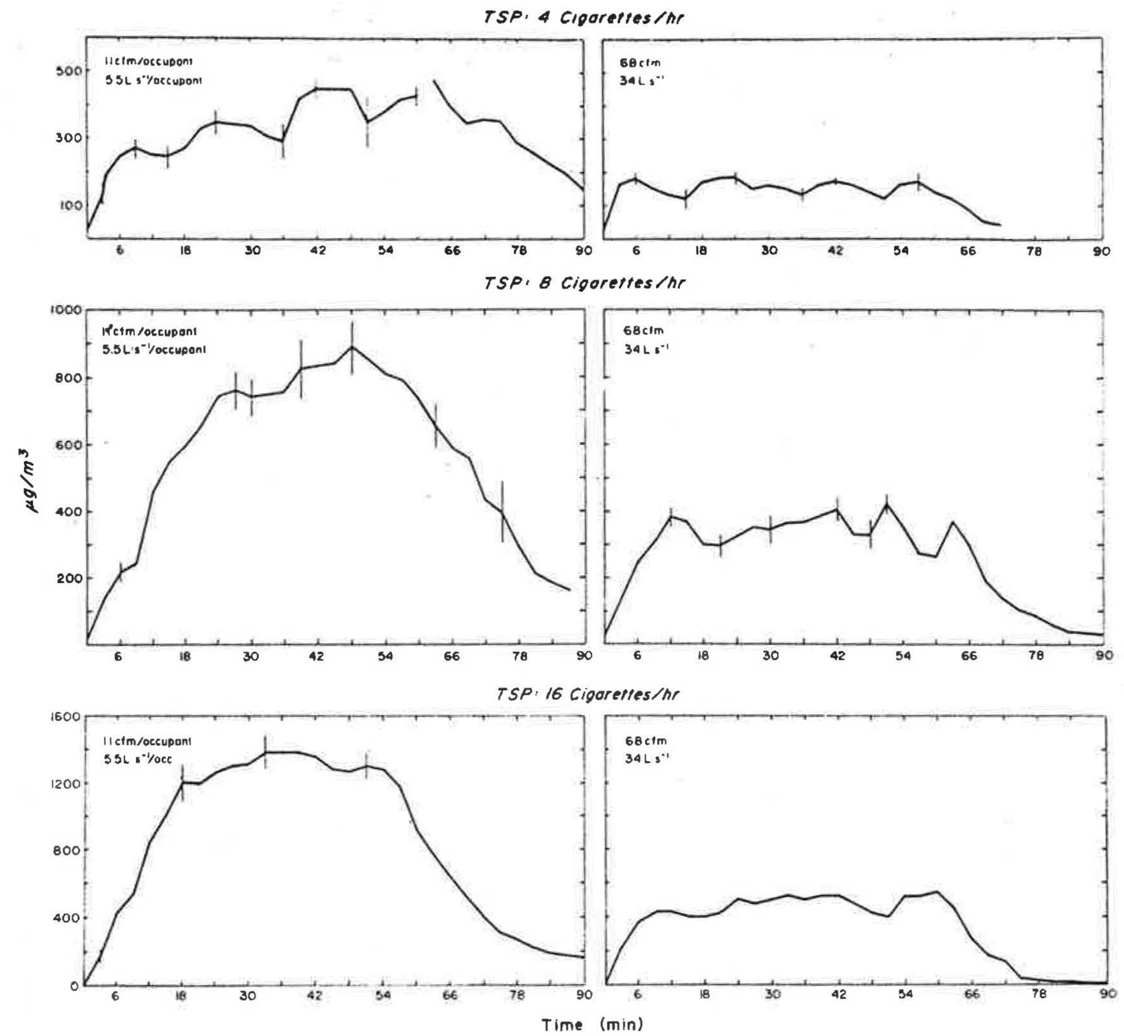


Fig. 11. Variation of total suspended particulate (TSP) mass concentration during smoking ($t$ = 0 to 60 min) and postsmoking segments for the lowest and highest ventilation rates, 5.5 and 34 $\ell$ $s^{-1}$ per occupant. The bars depict standard errors where the number of replicate sessions exceeded two. The average number of sessions equalled seven. Note that ordinate for sixteen cigarettes per hour differs by a factor of two from the ordinates for four and eight cigarettes per hour.

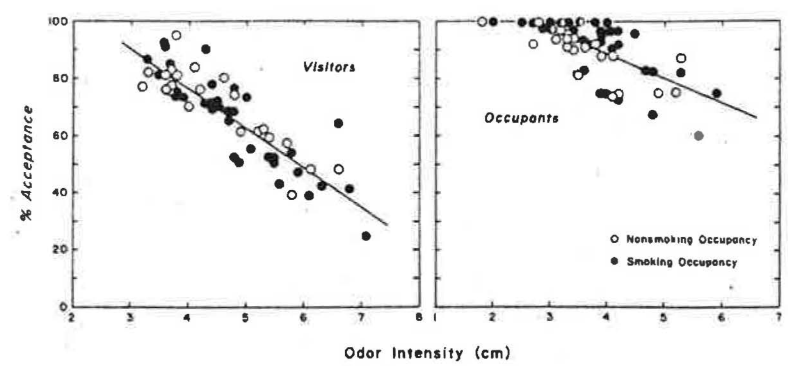


Fig. 12. Left: Showing the relation between acceptance and odor intensity (assessed by line marking) for visitors in the occupancy odor and tobacco smoke odor experiments. Right: Showing the relation between acceptance and odor intensity for occupants.

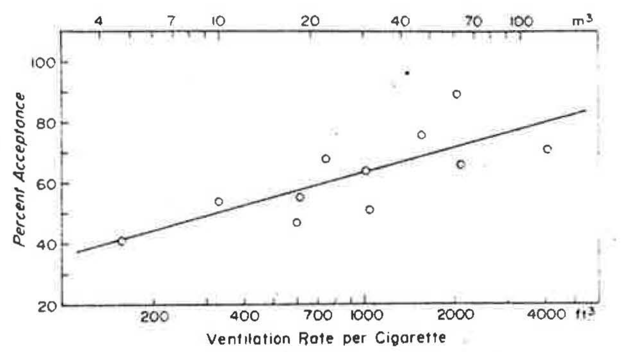


Fig. 13. Percent acceptance (data from Table 2) vs ventilation rate per cigarette during conditions of active smoking and moderate humidity.

$5\ m^3$ in the case of 16 cigarettes $h^{-1}$ and $5.5\ \ell\ s^{-1}$ per occupant to $122.4\ m^3$ in the case of four cigarettes $h^{-1}$ and $34\ \ell\ s^{-1}$ per occupant. An earlier investigation of Yaglou (1955) had implied that about $9\ m^3$ per cigarette would suffice. Some other investigations had implied the need for up to 10 times as much, $90\ m^3$ (Kerka and Humphreys, 1956). We chose combinations of smoking and ventilation that bracketed this range. Nevertheless, our results barely managed to reach the point of acceptability for 80% of visitors during a period of active smoking in conditions of moderate humidity. This outcome is quite apparent in Fig. 13 which depicts percent acceptance during smoking (data from Table 2) vs ventilation rate per cigarette. The regression line implies that $78–120\ m^3$ per cigarette would place acceptability in the region of 75–80%.

Field studies have implied that in places occupied by a reasonably large number of smokers and nonsmokers, approximately 10% of the occupants will be smoking at any given time (Repace and Lowrey, 1980). If we assume that cigarette smoke odor governs ventilation requirements entirely under conditions of smoking, then we could conclude that the required ventilation rate per occupant should equal 10% of the ventilation rate required per cigarette. For our results in the region of 75–80% acceptance, this would translate into $17.5–26.5\ \ell\ s^{-1}$ per occupant, assuming that a cigarette requires 7.5 min to burn.

The ASHRAE standard on indoor air quality now specifies two different ventilation rates in any given area (e.g. meeting room, theatre lobby), one for smoking occupancy and one for nonsmoking occupancy. (The previous edition of the standard had made no explicit recommendations for smoking vs nonsmoking occupancy.) The modal value for smoking occupancy across various types of areas equals $17.5\ \ell\ s^{-1}$ per occupant, about five times greater than the modal value for nonsmoking occupancy. Based on the results in Fig. 13, it would appear that 75% of occupants (mixed smokers and nonsmokers) would find the ASHRAE-recommended rate in smoking areas acceptable. Presumably, however, most of the discontented occupants would be nonsmokers (see Fig. 9). In order to achieve 80% acceptance, the rate would need to equal about $26.5\ \ell\ s^{-1}$ per occupant. Irrespective of whether the criterion for odor is set at 75 or 80%, smokers would account for almost 90% of the demand for ventilation during smoking occupancy even though they constitute only about one third of the adult population.

Measurements of particulate mass concentration made it clear that smoking will increase the particulate burden of nonsmokers considerably even at the highest practicable ventilation rates. The increment above background levels measured here ranged from a factor of about 3 to a factor of about 40. There exists no simple way to interpret the meaning of these increments. In most instances, the values exceeded the primary air quality standard of $260\ \mu g\ m^{-3}$ (24-h average) for outdoor air. Nevertheless, particulate matter outdoors, which arises primarily from the burning of fossil fuel, differs markedly from the tobacco aerosol both physically and chemically. Although ventilation can exert some control over particulate concentrations indoors, only suitable filtration can bring the indoor concentrations down to levels that would indisputably pose no hazard (see Leaderer *et al.*, 1983, for further consideration of this issue).

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