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VENTILATION REQUIREMENTS FOR CONTROL OF OCCUPANCY ODOR AND TOBACCO SMOKE ODOR: LABORATORY STUDIES FINAL REPORT

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EXECUTIVE SUMMARY

Requirements for ventilation of occupied spaces have long rested largely on the need to control odors. Quantitative studies over the last half century have dealt specifically with occupancy (body) odor and tobacco smoke odor. These two form extremes on a continuum of severity. Laboratory experiments by Yaglou and colleagues in the 1930's implied that occupancy odor was controllable with ventilation rates that ranged from only about 7 cfm (3.5 $L \cdot s^{-1}$) per occupant under uncrowded conditions (more than 500 cu.ft. or 14 m^3 per occupant) up to about 25 cfm (12.5 $L \cdot s^{-1}$) per occupant under crowded conditions (100 cu.ft. or 3 m^3 per occupant). A reinspection of these rates should, it seemed, address the question of why required ventilation rate per occupant increased progressively with increases in the number of persons in a space. Our experiments on occupancy odor addressed this question.

Tobacco smoke odor has generally seemed controllable only with relatively large amounts of ventilation, though quantitative estimates have varied by a factor of almost ten. The gases and particulate matter emitted during cigarette smoking not only give rise to odor and irritation but may also give rise to unhealthful conditions. Possible health effects of these contaminants indoors have become apparent only gradually over the last 10-20 years. Estimates of ventilation requirements for tobacco smoke now need to derive both from subjective measures of acceptability and objective measures of the notable contaminants.

In order to investigate ventilation requirements under approximately ideal conditions, we constructed an aluminum-lined environmental chamber with excellent control over environmental conditions and a ventilation system that provided rapid and uniform mixing of air. The chamber could seat up to 12 occupants comfortably. Psychophysical experiments on occupancy odor explored 47 different combinations of occupancy density, temperature and humidity, and ventilation rate. The experiments collected judgments both from visitors, who smelled air from the chamber only once every few minutes, and from occupants, who remained in the chamber for an hour at a time. Visitors actually sampled the air from a sniffing box attached to the chamber and which obviated the need to enter the chamber.

The judgments of visitors revealed that occupancy odor increased only gradually over time and rarely reached very high or objectionable levels. Judgments of occupants also revealed rather minor dissatisfaction. Only during combinations of high temperature and humidity did objectionability become more than a minor issue to either group. Under conditions of moderate humidity, about 75-80% of visitors and more than 90% of occupants found the odor acceptable when ventilation rate equalled only 5-10 cfm (2.5-5 $L \cdot s^{-1}$). There seemed no need for greater ventilation per person during high occupancy density (12 persons in the chamber) than under lower density (8 or 4 occupants). Perhaps inadequate control over environmental conditions or poor clearance of contaminants account for why the widely cited laboratory research of Yaglou and colleagues implied the need for vastly more ventilation per occupant under conditions of crowding. Our results imply the possibility of energy savings through reduced ventilation in places where occupancy odor is the principal "contaminant."

Experiments on cigarette smoking explored rates of 4, 8, and 16 cigarettes per hour under various environmental conditions and with ventilation rates as high as 68 cfm (34 $L \cdot s^{-1}$) per occupant. Measurement of carbon monoxide and particulate matter supplemented the psychophysical judgments of visitors and occupants. As soon as occupants lit cigarettes in the chamber, the odor level increased dramatically. At ventilation rates far greater than necessary to control occupancy odor, the odor from cigarette smoking remained quite intense. In general, the odor proved impossible to control adequately even with a ventilation rate of 68 cfm (34 $L \cdot s^{-1}$) per occupant (4 occupants) and even when only one occupant smoked at a time. As in the case of occupancy odor, a combination of high temperature and humidity exacerbated the odor problem. Interestingly, conditions that failed to control odor also failed to control particulate mass concentration to levels considered acceptable outdoors (75 $\mu g/m^3$). For smoking rates and ventilation rates considered typical of real world conditions, particulate mass concentration generally exceeded 200 $\mu g/m^3$. Carbon monoxide reached unacceptable levels only under the most extreme conditions of smoking.

Preliminary experiments on contaminant control implied that activated carbon or a half-and-half mixture of activated carbon and activated alumina impregnated with potassium permanganate would control occupancy odor readily. Use of such granular media could clearly serve to decrease reliance on outdoor air. Particle filtration of smoke-laden air proved rather unsuccessful for elimination of tobacco smoke odor. The exact role of particles in the creation of that odor nuisance deserves greater attention. An experiment on how tobacco smoke odor decays in an unventilated chamber revealed an extremely gradual decline over the course of hours. The decline nevertheless seemed roughly to parallel changes in the number and concentration of organic materials assessed by gas chromatography.

The primary conclusions regarding the subjective acceptability of tobacco smoke odor came from a mixed group of both smokers and nonsmokers. Consideration of nonsmokers alone uncovered a very strong intolerance for cigarette smoke odor. This occurred even though the nonsmokers did not have to sit in the room during smoking. Smokers exhibited considerably greater tolerance. Because of this difference in tolerance between groups, it seems reasonable from the standpoint of energy efficiency to set aside small well-ventilated spaces for smoking and to prohibit smoking in other spaces indoors. Without such an arrangement, the smoker could account for more than 90% of the ventilation in a building and might still leave a substantial fraction of nonsmokers dissatisfied with indoor air quality.

GENERAL INTRODUCTION

A sensitive chemical analysis of the air in a building will characteristically reveal a large number of organic substances, many at concentrations too low to have discernible biological impact. If the concentrations of the chemicals increase, the first sign of their presence may occur via the sense of smell. The air may become odorous. In the general absence of any better or faster indicator, smell will serve as the principal means 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. The cost of ventilation, on the average more than 25% of the operating cost of a building, increases proportionally with the cost of energy and therefore provides a strong incentive to search for energy efficiency.

A previous report reviewed the literature relevant to odor perception, odor control, and ventilation (1). The report highlighted prospects for research that might point to ways to achieve both acceptable air quality and energy efficiency in ventilation. The present report provides an account of laboratory research stimulated by that review. The report focuses on ventilation requirements for occupancy odor (Part 1) and tobacco smoke odor (Part 2), and offers some preliminary observations on how filtration may aid ventilation (Part 3).

PART 1: OCCUPANCY ODOR

INTRODUCTION

In the nineteenth century, some public health specialists expressed concern over occupancy of any place with "occupancy" odor, even when the odor arose from healthy persons. The fear derived from the undocumented suspicion that disease might arise in crowded places by means of biological emanations known variously as anthropotoxin, mobific matter, and crowd poison. Such fear subsided during the twentieth century, in part because of more enlightened views regarding the transmission of disease and in part because sanitation and personal hygiene made crowded places less threatening (2). Concern with odors still persists, but with less emphasis on disease and more emphasis on comfort.

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 C. P. Yaglou, applied simple psychophysical scaling to the question of how the level of occupancy odor depended on ventilation. In the most ambitious study, Yaglou, Riley, and Coggins (3) charted odor as a function of density of occupancy (i.e., number of people in a room), age (child vs adult), socioeconomic status ("laborers" vs medical school staff and students), personal hygiene (frequent vs infrequent bathing), and ventilation, ranging from 5 cfm (2.5 $L \cdot s^{-1}$) per occupant to 30 cfm (15 $L \cdot s^{-1}$) 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. 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. Figure 1 shows that relation derived for adults with normal hygiene (4). As the number of people in Yaglou's 1410 cu.ft. chamber increased from 3 to 7, the required amount of fresh air per occupant increased from 7 cfm (3.5 $L \cdot s^{-1}$) to 16 cfm (8 $L \cdot s^{-1}$). For 14 occupants, the required amount of fresh air equalled 25 cfm (12.5 $L \cdot s^{-1}$) per occupant.

The estimates of odor level that led to the construction of curve C in Fig. 1 came from a few observers who entered the chamber momentarily from a fresh room. It seems strange that ventilation requirements should have failed to vary proportionally

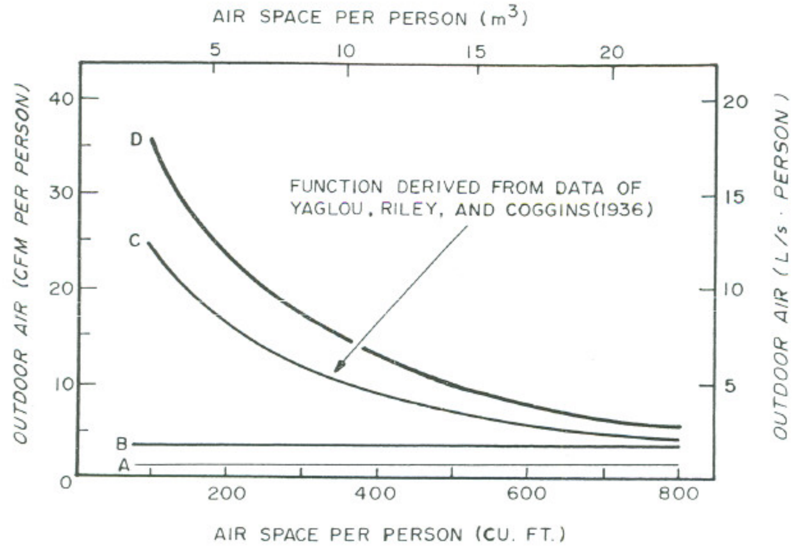


Fig. 1. The relation between air space per person and ventilation requirements under four criteria:

A) maintenance of sufficient oxygen ($\bar{>}$ 20%),
B) control of carbon dioxide ($\leq$ 0.6%),
C) control of odors during sedentary, nonsmoking occupancy, and
D) control of odors during smoking occupancy.

Curve C has a foundation in psychophysical data, whereas curve D does not.

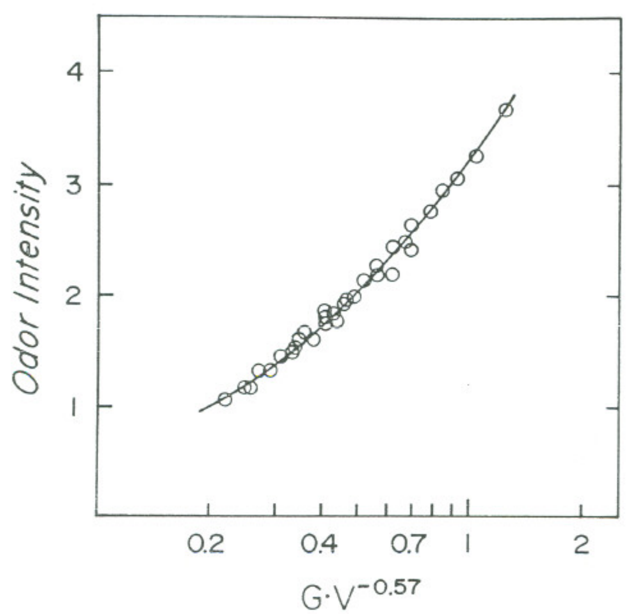


Fig. 2. Showing how the occupancy-odor judgments obtained by Yaglou, Riley, and Coggins (3) fall along a single function when plotted against rate of odor generation (G, expressed as number of persons in an environmental chamber) divided by ventilation rate (V, expressed in cfm) raised to the 0.57 power.

with density of occupancy, an outcome that would have allowed the rate per person to remain constant with changes in density. Yaglou recognized the anomaly and suggested two possible causes: 1) progressive inefficiency in the clearance of contaminants as nominal ventilation rate increased, and 2) instability of occupancy odor, i.e., rapid decay of this particular odor even without dilution (5). Figure 2 depicts odor level in Yaglou's experiments plotted as a function of contaminant generation rate divided by nominal ventilation rate raised to the 0.57 power. We arrived at the exponent 0.57 empirically during an effort to discover whether any single function might describe all of Yaglou's estimates. The success of the effort and the value of the parameter appear compatible with the notion that the efficiency of clearance from Yaglou's chamber decreased progressively with increases in nominal ventilation rate. In almost all of his experiments, the only air supplied to the chamber was ventilation air rather than a proportional mixture of ventilation air and recirculated air. Had the chamber maintained its efficiency at all ventilation rates, then the odor judgments would have fallen along the same function when plotted against generation rate divided by ventilation rate to the 1.0 power. When viewed in this light, Yaglou's results may seem to have only precarious generality. His experimental chamber possessed a ventilation system designed for rather good clearance of contaminants, but Yaglou offered no direct verification of ventilation rate. He computed the rate from the linear velocity of air entering through an orifice. Modern instruments that can monitor tracer gases continuously now offer a ready means of verification (6).

Yaglou's estimates of ventilation requirements have withstood the test of time. That is, few persons have argued that the 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 the rate necessary (7).

In an effort to build upon previous work, we too built an environmental chamber for the exploration of ventilation requirements to control occupancy odor and other notable contaminants (see Fig. 3) (8). The first part of this report deals almost exclusively with occupancy odor, though it gives slight comparative attention to tobacco smoke odor. The second part deals specifically with ventilation requirements for tobacco smoke. Our chamber permitted precise control of environmental conditions, more or less unspecified in Yaglou's experiments. The room thereby permitted an exploration of ventilation requirements over conditions ranging from the current recommended winter-time level of 68F (20C) with relatively low humidity to the current summer-time recommended level of 78F (25.5C) with high humidity. The capability to verify ventilation rates by means of a tracer gas also permitted a reinspection of whether ventilation requirements should vary with occupancy density under reasonably crowded conditions. We concerned ourselves primarily with crowded conditions of the sort encountered in classrooms, public dining rooms, conference rooms, and waiting rooms, i.e., more than 30 persons per 1000 ft^2 (93 m^2). Under less crowded conditions, ventilation requirements based on occupancy odor rapidly converge on those based on carbon dioxide (Fig. 1). Psychophysical experiments therefore impart less important information under uncrowded conditions of occupancy. Our experiments also concerned themselves with how occupants (e.g., persons who occupy a chamber for an hour) might differ from visitors (e.g., persons fresh from another room) in their assessment of the environment.

Facilities

Figure 4 presents a schematic view of the environmental chamber with associated control equipment. The box on the right, actually a cross-sectional schematic of

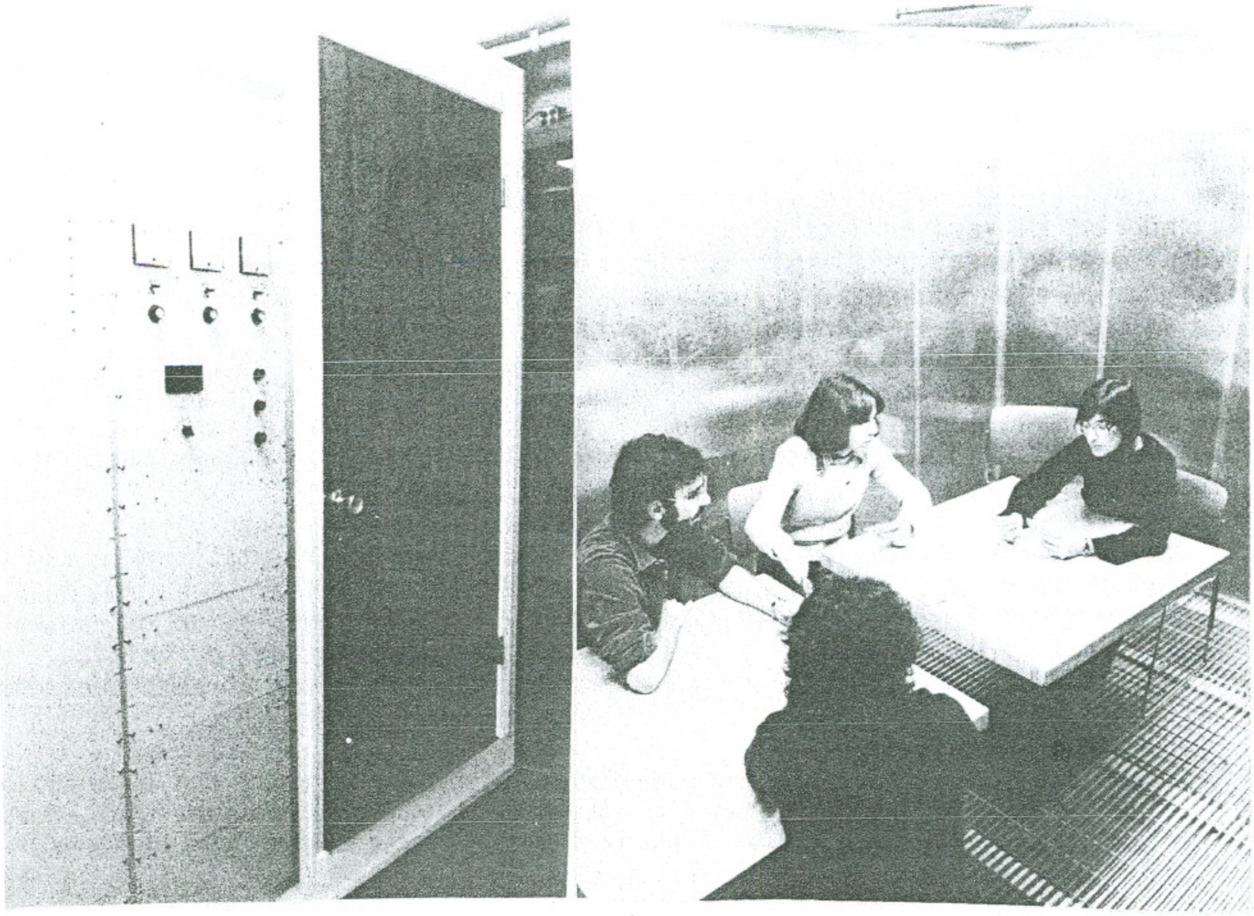


Fig. 3. Left side shows the outer door of the environmental chamber and the panel to indicate and control environmental conditions. Right side shows four occupants in the aluminum-lined chamber.

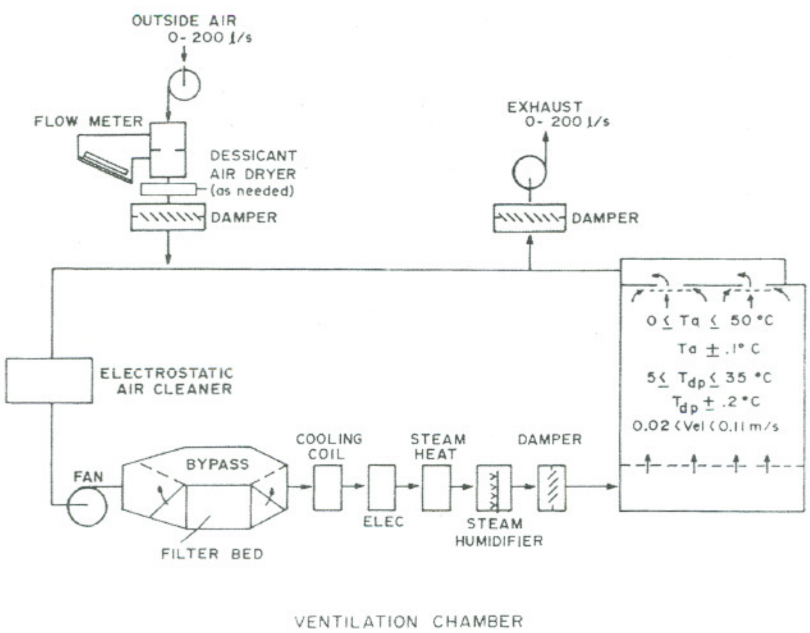


Fig. 4. Schematic view of environmental chamber and control equipment. Arrows in box at right portray the flow of air from the plenum beneath the floor to the return ducts in the ceiling.

the chamber itself, displays within it the range of operating conditions. All ductwork and internal surfaces were constructed of aluminum. This minimized potential gas-surface reactivity and permitted easy cleaning of accessible places. Even the floor comprised aluminum sheet overlaid with an aluminum grating. The entire floor served an important function as a diffuser. This 11-m^2 area contained 13,900 perforations across its surface. Air entered the chamber via a plenum beneath the floor and streamed upward through the perforations. The arrangement allowed a volume flow of up to 2000 cfm (1000 $L \cdot s^{-1}$) through the space (i.e., one exchange every 40 sec) with low linear velocity. In general, our experiments employed the maximum flowrate. Such conditions led to very rapid mixing and, accordingly, relative homogeneity of the composition of air in the chamber. A variable percentage of the 2000 cfm (1000 $L \cdot s^{-1}$) passing through the chamber could comprise fresh, ventilation air. If we wished to deliver, say, 20 cfm (10 $L \cdot s^{-1}$) of ventilation air per occupant to 12 occupants, we would take in 240 cfm (120 $L \cdot s^{-1}$) from outdoors and would deliver 1760 cfm (880 $L \cdot s^{-1}$) via recirculation for a total of 2000 cfm (1000 $L \cdot s^{-1}$).

Another feature of the chamber was a sniffing station, an aluminum box (0.11 m^3) fed with air from one of four return-air ducts. Air passed through this box and eventually went back into the return duct. The box enabled persons to judge the quality of the air in the chamber without the need to enter it. This set-up eliminated the large dilution and disturbance that would have occurred if visitors (judges) had entered the chamber every few minutes. In order to judge the air, the visitor merely opened the sliding door of the box and inhaled the air moving through it (see Fig. 5).

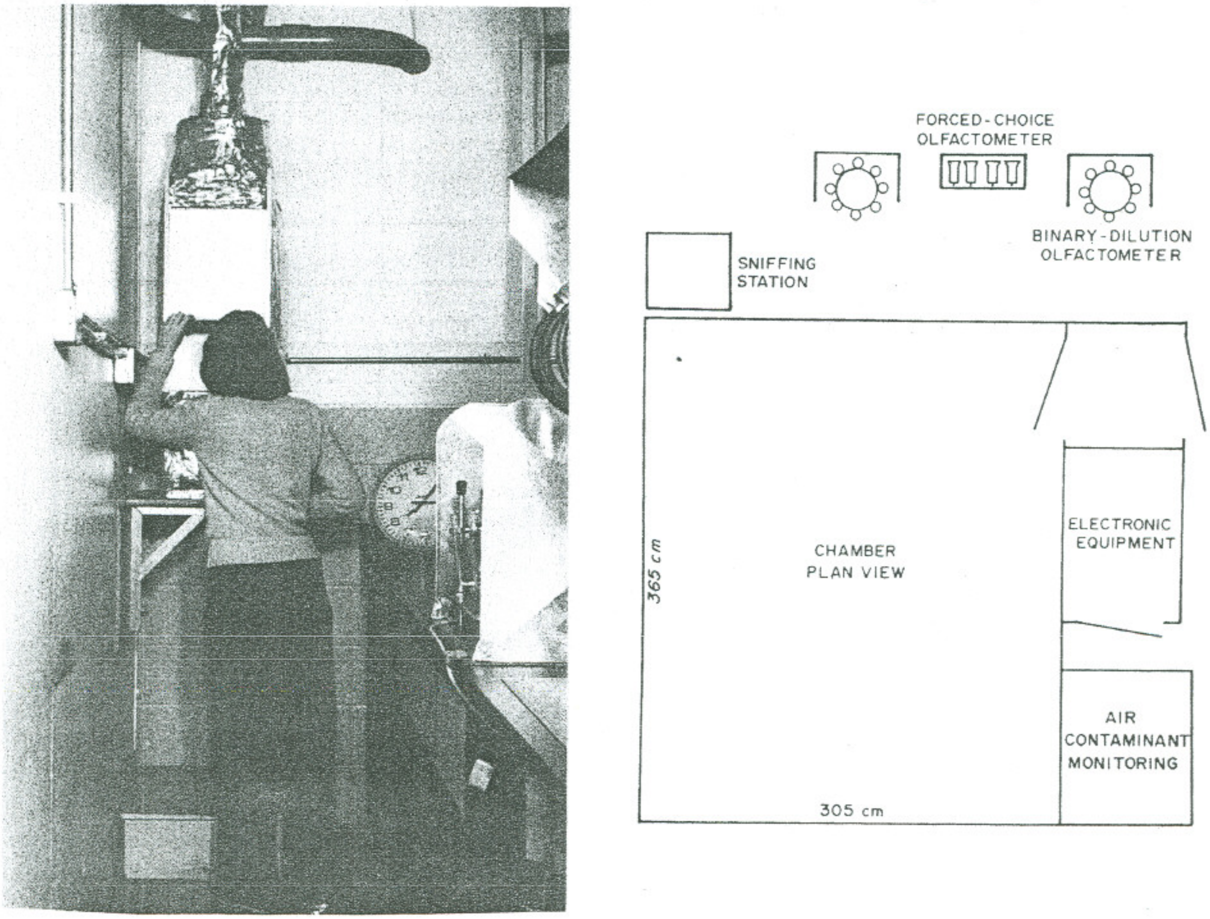


Fig. 5. Left side shows a "visitor" raising the sliding door of the sniffing station. The clock allowed the person to record the time of the visit. Right side shows a plan view of the chamber, sniffing station, and olfactometers. Occupants entered the chamber through the two doors shown in the upper corner.

Calibration of ventilation rate, which took place during unoccupied periods, employed carbon dioxide monitored by a Beckman LB-2 Infrared Analyzer. This gas was injected until it reached a concentration of about 1%. The rate of decay under conditions of ventilation signalled ventilation rate. The analyzer used to calibrate ventilation rate also served to monitor expired carbon dioxide during human occupancy.

Participants

One hundred sixty-five persons participated in the study. Some came from the Yale community, but many came from the greater New Haven community. Although the median age equalled only 22.5 yrs (range: 18 to 62 yrs), a relatively large number of persons over 30 yrs participated very frequently. The number of 3-hr sessions per person ranged from 1 to 45 with a median of 5.

Procedure

The main factors of the investigation included: three levels of occupancy (4, 8, and 12 occupants), four ventilation rates (5, 10, 15, and 20 cfm per occupant; 2.5 to 10 $L \cdot s^{-1}$ per occupant), and four environmental conditions (20C, RH $\leq$ 50%, denoted moderate humidity; 23C, moderate humidity; 25.5C, moderate humidity; and 25.5C, RH $\geq$ 70%, denoted high humidity). Each of 47 combinations of these factors received attention (see Fig. 8 for the combinations). A typical session began with psychophysical scaling of a reference odorant. Each participant judged eight concentrations of 1-butanol by means of the psychophysical scaling method known as magnitude estimation (9). 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 (Fig. 6) (10). This standard describes a procedure to measure suprathreshold odor intensity via matching. In principal, a person can always find a concentration of butanol that falls close to the perceived intensity of any given test odorant. The numerical scaling employed in the present case served to familiarize the participant with the range of available intensities and to allow the participant to erect an internal numerical scale for use during the main part of the

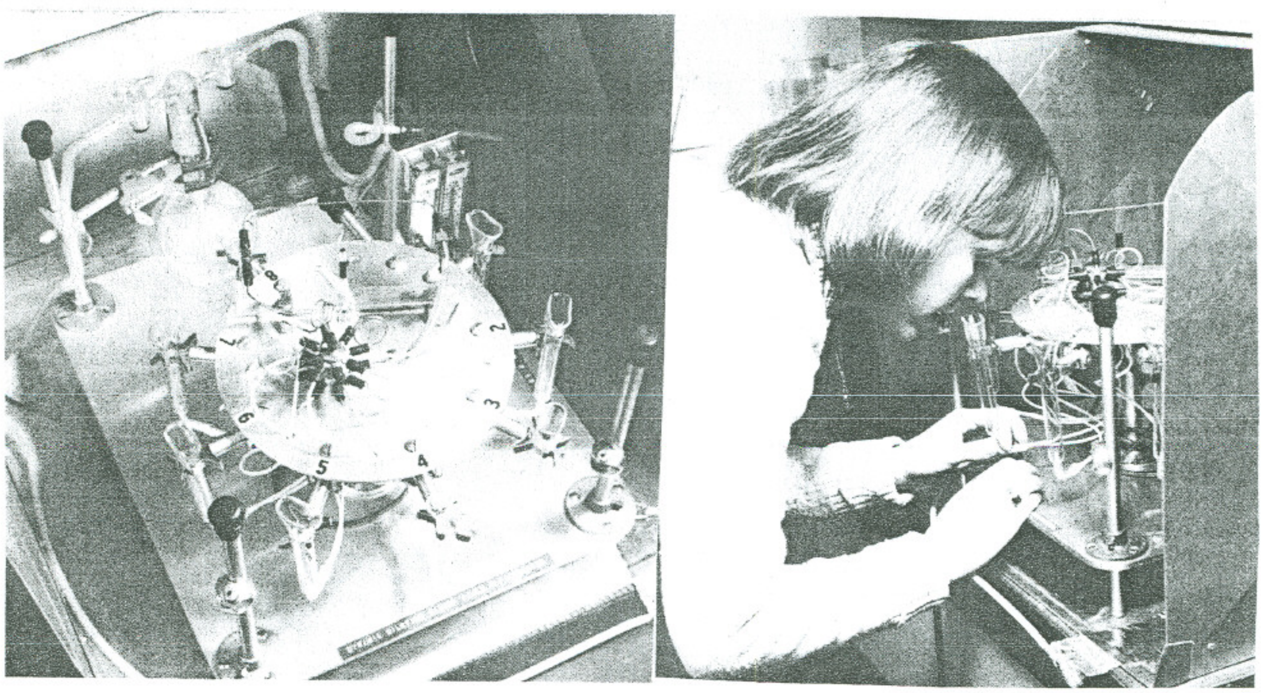


Fig. 6. Left side shows a Dravnieks binary dilution (butanol) olfactometer. The circular plate with the attached nozzles rotates to allow any one to be available to the participant. Right side shows a participant putting her nose into position for a sniff. Flowrate emanating from each nozzle equalled 160 mL per min.

session. The actual procedure for the initial portion entailed smelling the various concentrations of butanol one-by-one in irregular order and assigning suitable numbers to represent intensity. According to the instructions given to the participant, a concentration that smelled twice as strong as another should receive a judgment twice as large. A concentration that smelled one-third as strong should receive a judgment one-third as large. And so on.

After the participants had completed the judgments of butanol, some persons (denoted occupants) entered the environmental chamber and others (denoted visitors) remained in a waiting room. The occupants dressed as they pleased. Because this part of the study took place during the fall, spring, and summer, occupants tended to wear light clothing. In some instances, however, persons would arrive with sweaters or light jackets to wear during sessions run at 20C.

Shortly after the occupants had entered the chamber, the visitors in the waiting room began, one-by-one, to judge the odor at the sniffing station. This required about a 25-m walk through a generally unoccupied corridor.

When the visitor sniffed the air at the station, he or she assigned the occupancy odor a magnitude estimate from the scale previously generated from judgments of butanol. This maneuver served, we hoped, to capture the immediate impression. The participant wrote this number, along with the exact time of the judgment, on a data sheet carried on a clipboard. The person then moved only a couple of paces to the location of the butanol olfactometer and sought to find a port that matched the intensity of the occupancy odor. The person had the opportunity to signify half-steps (e.g., 3.5), when the intensity seemed to fall between adjacent concentrations (e.g., ports 3 and 4). Port number, termed butanol level, served as the primary index of intensity throughout the investigation.

The visitor returned to the waiting room after a judgment and told the next person in line to proceed to the sniffing station. The procedure continued for an hour and yielded four to nine judgments per person, depending on the number of participants. Each of the 47 combinations of factors was run until we had judgments from about 25 visitors. Normally 6-8 visitors participated in a session.

At the time of the final judgment of a session, the visitor added a third and fourth component to the estimate of intensity of occupancy odor. The third component involved marking a 13.5 cm line where the left end equalled no odor and the right end a very strong odor. The fourth 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. See Fig. 7 for sample data sheet.

Whereas visitors made judgments throughout an hour, occupants inside the chamber made judgments only during the final moments of occupancy. These judgments entailed marking lines that comprised unipolar scales for the attributes odor and irritation (13.5-cm lines) and bipolar scales (27-cm lines with a zero at the midpoint) for temperature (cold-hot), humidity (dry-humid), and stuffiness (drafty-stuffy). Accompanying letters (A, NA) allowed judgments of acceptability or unacceptability for each attribute (see Fig. 7).

Visitor's Data Sheet

Name: ______________________ Date: ______________________

Matching

Time	Mag.Est.	Port No.

Time	Mag.Est.	Port No.

Odor A NA

Time: __________ 0 ______________________________

Odor A NA

Time: __________ 0 ______________________________

Occupant's Data Sheet

COMFORT SCALES (Place mark on line)

Name ______________________

Date ______________________ Time ______________________

Circle One
A NA

Too Cold ______________________________ Too Hot

Circle One
A NA

Too Dry ______________________________ Too Humid

Circle One
A NA

Too Drafty ______________________________ Too Stuffy

Odor A NA
____

Irritation A NA
____

Fig. 7. Top shows the data sheet that visitors carried with them and used to record their judgments. Successive judgments were entered sequentially. The final judgment in a 1-hr period included marking the line denoted Odor and circling A (acceptable) or NA (not acceptable). Bottom shows scales that occupants marked during the final moments of a 1-hr period of occupancy.

RESULTS

Odor Intensity

Figure 8 shows how odor varied during 1-hr periods of occupancy for 47 combinations of density 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. Each function comprises four data points plotted at 15-min intervals. A data point arose from judgments that an average of 26 persons (standard deviation = 5) made 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 upon initial examination: 1) mean levels 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 2-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 varied undoubtedly with the occupants' diet, personal hygiene, amount of clothing, and those many other factors that will change the profile of organic vapors that emanate from human bodies. (The third section of this report will deal in part with analyses of organic materials present during mere occupancy and during smoking.) In an effort to minimize certain possible overwhelming, extraneous determinants of odor level, we had asked our participants to abstain from the use of fragrances other than underarm deodorant and to abstain from eating in the chamber. Occasionally, the chamber would smell of perfume that had previously adsorbed to a person's clothes (particularly sweaters, which are commonly worn several times between washings), of a food or beverage (e.g., beer) taken before occupancy, or of candy or gum consumed during the session in spite of our wishes. Such fluctuations undoubtedly represent a much compressed version of those that occur in everyday life.

Fluctuations in the functions become less of a burden when the data are averaged in such a way as to focus on specific questions, such as "How does odor vary with the number of persons in the chamber?" and "How does odor vary with environmental conditions?" Figure 9 depicts butanol matching functions averaged across all four environmental conditions for each density of occupancy. The outcome, unlike that of Yaglou and colleagues (3), implied no consistent effect of density. Although solid in this outcome, the data also give rise to the suspicion of some foreshortening in the range of responses, viz., a tendency to give a judgment of 2.0 or a little higher even when the chamber may have had virtually no odor. The tendency to foreshorten the range of the matching continuum appears ubiquitously in matching experiments (11). It is noteworthy, however, that some participants failed to perceive odor at level 1 during the scaling at the beginning of each session. Hence level 2 was the lowest detectable level for some fraction of the participants. Some persons may have chosen this innocuous level just to demonstrate their involvement in the task at hand. Other persons undoubtedly matched it quite accurately to their impression of odor at the sniff box.

The magnitude estimations yielded about the same picture as that shown by matching. To illustrate, the upper part of Fig. 10 shows the butanol matching functions from Fig. 9 plotted in linear coordinates and the lower part shows the corresponding magnitude estimations. Scaling of the eight ports of butanol at the beginning of each session revealed that magnitude estimation was related to the concentration of this reference odorant by a power function with an exponent of 0.40 (see Fig. 11).

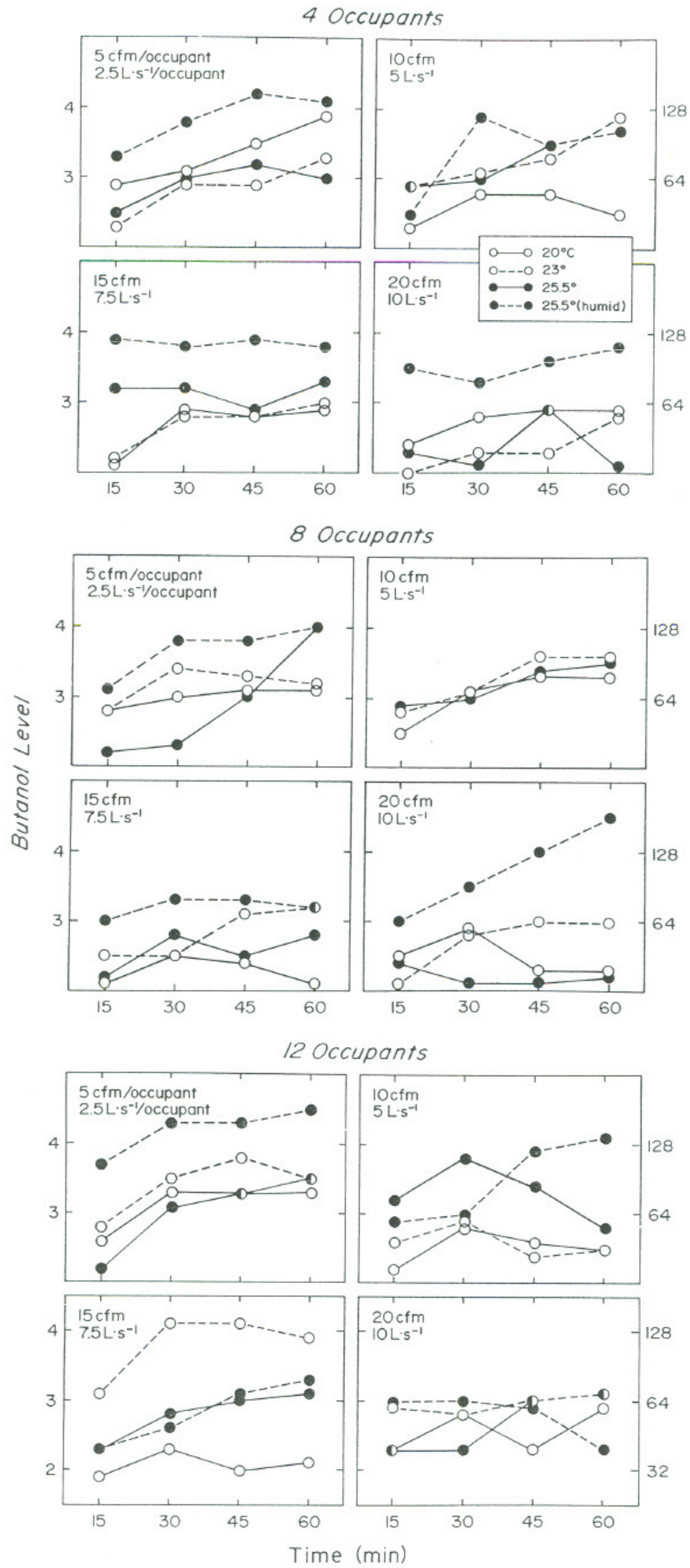


Fig. 8. Butanol matching functions obtained under 47 conditions of occupancy.

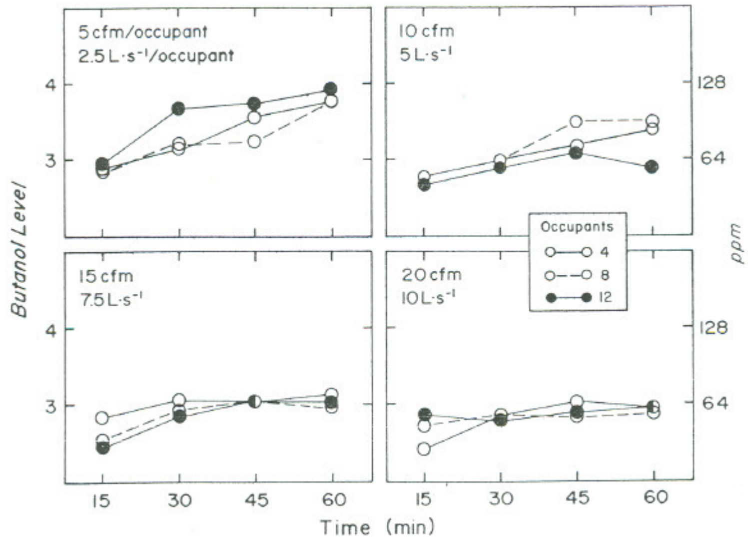


Fig. 9. Butanol matching functions taken across environmental conditions in order to explore whether odor level varied systematically with number of occupants at various ventilation rates ranging from 5 cfm (2.5 $L \cdot s^{-1}$) to 20 cfm (10 $L \cdot s^{-1}$) per occupant.

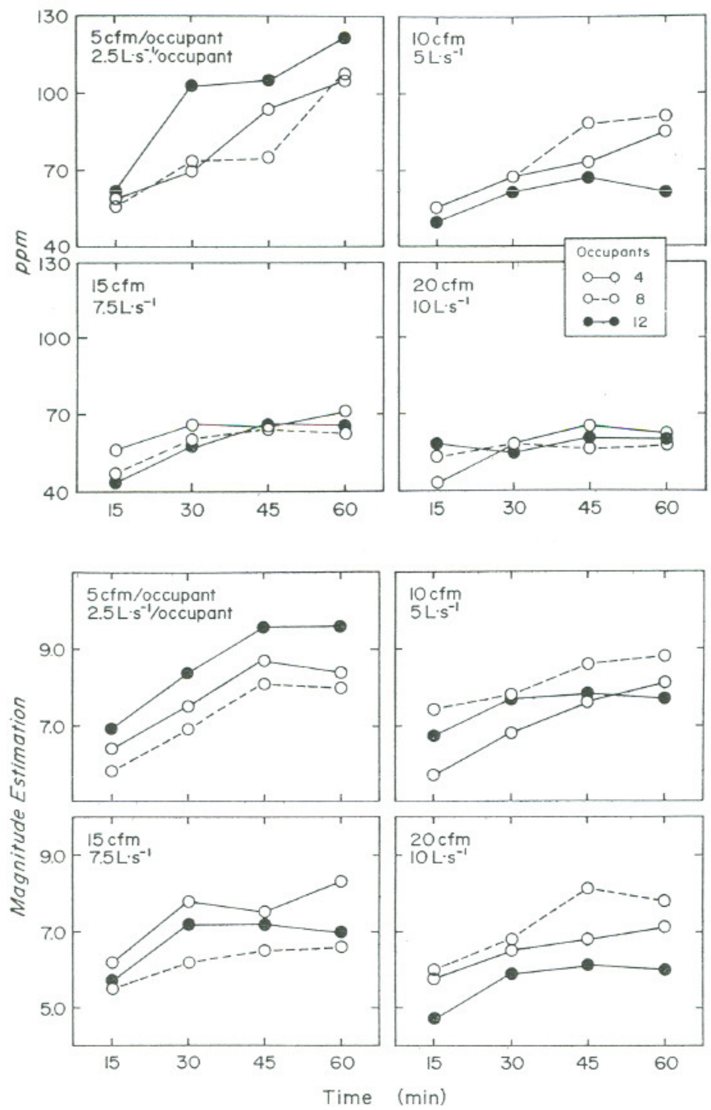


Fig. 10. Upper part depicts butanol matching functions taken across environmental conditions and plotted in linear coordinates. Lower part depicts corresponding magnitude estimations. For both sets of data, standard errors equalled about 15% of the mean.

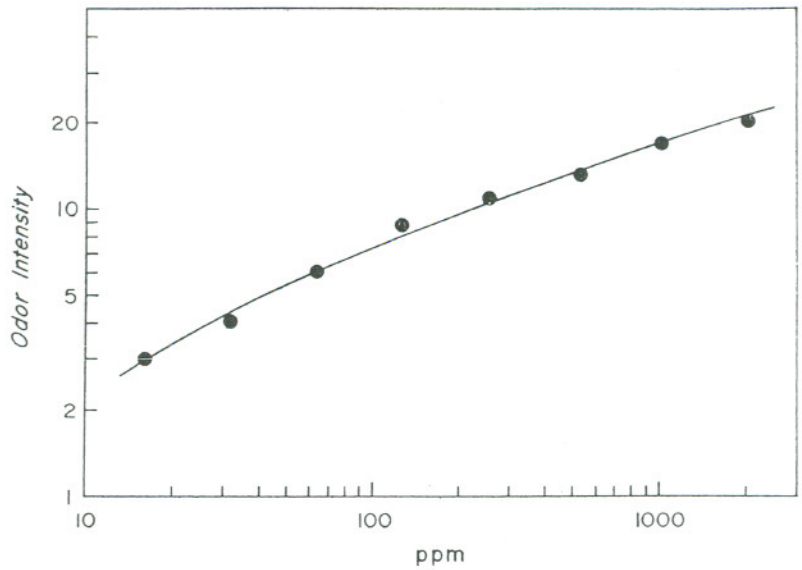


Fig. 11. Psychophysical function for the reference odorant butanol erected from magnitude estimations rendered at the beginning of each experimental session. The fitted function conforms to the equation $\psi = k(\phi - \alpha)^{\beta}$ where ψ refers to perceived magnitude and ϕ to concentration. The parameter α equalled 6 ppm and the exponent β equalled 0.40

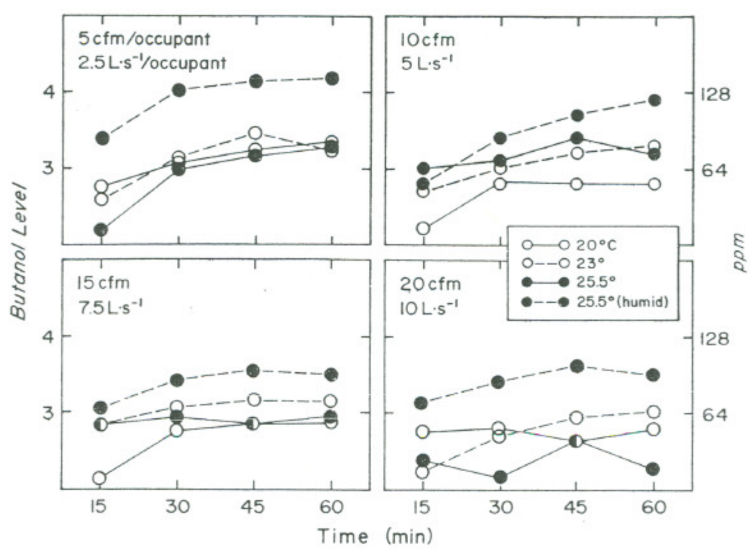


Fig. 12. Butanol matching functions taken across number of occupants in order to explore whether odor level varied systematically with environmental conditions.

Whereas Fig. 9 depicts results taken across environmental conditions and thereby focuses on occupancy density, Fig. 12 depicts results taken across number of occupants and thereby focuses 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 a more intense odor than conditions of moderate humidity. The influence of high humidity amounted to 0.6 scale units on the average which translates into an increment of 50% in matched concentration of butanol.

Since density had no apparent effect, Fig. 13 presents composite functions taken across all three densities but 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. These functions offer the most stable estimate of how odor varies with time. All four functions in the three panels seem close to steady state at 60 min.

Odor Acceptability

In order to find meaning in the levels of odor intensity achieved, we can refer to the relation between acceptability and odor. The function in Fig. 14 arose from the final judgments made in a session. The relation reveals that visitors deemed even the lowest level (port no. 1) only 85% acceptable. The visitors found levels 2 and 3 acceptable 80% of the time. Between levels 3 and 4, acceptability dropped sharply and continued to plummet as the matching level approached 8.

An absence of clear level dependency suggests that matching levels 1 through 3 may reflect merely "noise-level" dissatisfaction that would occur if odor level ever exceeded threshold. Butanol matching functions obtained with ventilation rates of 5 and 10 cfm (2.5 & 5 $L \cdot s^{-1}$) per occupant, however, exceeded level 3. These functions raise the question of how high odor must climb before it fails to meet a reasonable criterion of acceptability. According to the acceptance function, the odor levels achieved with 5 and 10 cfm (2.5 and 5 $L \cdot s^{-1}$) per occupant would fall at about 70% and 78%, respectively.

Table 1 offers a more detailed view of how odor acceptability varied across conditions. 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 found the environment more odorous than occupants. Nevertheless, the occupants still judged the high humidity condition much more intense than the moderate humidity conditions (Fig. 15). So did the visitors. Percent acceptance seemed to track intensity rather closely. Among the visitors, acceptance typically fell a bit below or above 80% when humidity was moderate. Two notable exceptions included 8 occupants at 10 cfm (5 $L \cdot s^{-1}$) per occupant and 12 occupants at 5 cfm (2.5 $L \cdot s^{-1}$) per occupant. In these instances, acceptability fell to only 60%. At high humidity, visitors found the odor less than 70% acceptable on the average.

Using the data in Table 1, a simple linear regression of percent acceptance (A) on intensity (I) yielded the following: $A = -12.4\ I + 126$, $r = 0.87$, for visitors and $A = -7.9\ I + 118$, $r = -0.74$ 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 though the visitor understandably set a more stringent criterion than the occupant (see Table 1).

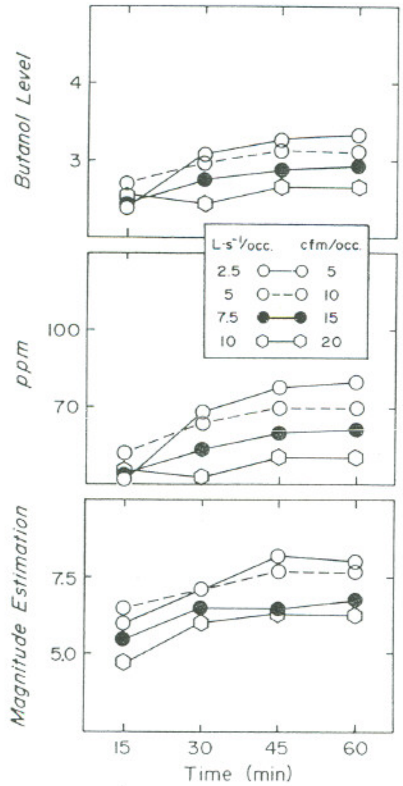


Fig. 13. Top and middle panels depict (on logarithmic and linear ordinates, respectively) butanol matching functions taken across number of occupants and across temperatures, but excluding the humid condition at 25.5C. Bottom panel depicts corresponding magnitude estimations.

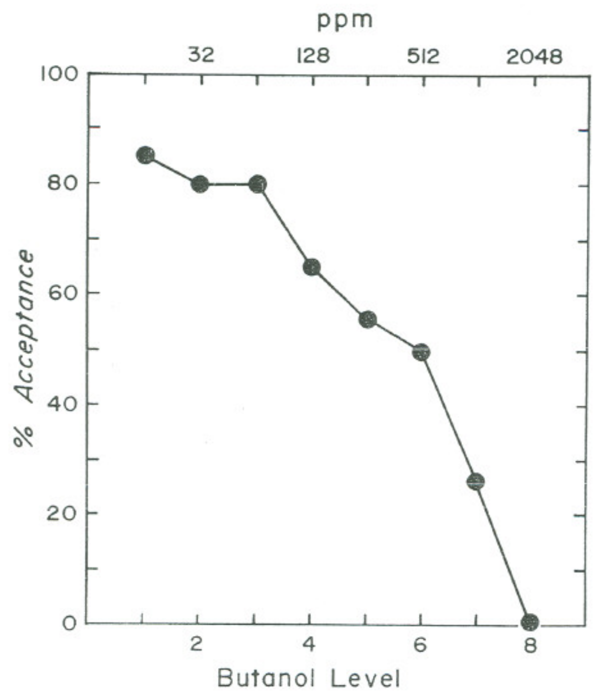


Fig. 14. Showing how acceptance of occupancy odor to visitors varied with equivalent (i.e., matched) level of butanol. The judgments were accumulated across all conditions. As the functions in Fig. 8 imply, the bulk of the intensity judgments fell between butanol levels 2 and 5. Nevertheless, most conditions elicited some individual judgments outside this range.

Table 1. Perceived Intensity (Indicated via Line-Marking) and Acceptability Obtained from both Visitors and Occupants during the Final Moments of the 1-hr Periods of Occupancy.

		Odor Intensity Scale (cm)		% Acceptance	
		Visitors	Occupants	Visitors	Occupants
Four Occupants					
5 cfm* ($2.5\ L\cdot s^{-1}$)*	Moderate RH	3.6**	2.9	76	95
	High RH	5.8**	5.2	39	75
10 cfm ($5\ L\cdot s^{-1}$)	Moderate RH	3.8	2.7	81	100
	High RH	3.7	4.2	76	75
15 cfm ($7.5\ L\cdot s^{-1}$)	Moderate RH	3.7	3.3	77	94
	High RH	4.9	4.9	61	75
20 cfm ($10\ L\cdot s^{-1}$)	Moderate RH	3.2	2.3	77	100
	High RH	4.7	3.2	67	100
Eight Occupants					
5 cfm ($2.5\ L\cdot s^{-1}$)	Moderate RH	4.0	2.4	70	100
	High RH	6.6	5.3	48	87
10 cfm ($5\ L\cdot s^{-1}$)	Moderate RH	5.2	3.2	61	92
15 cfm ($7.5\ L\cdot s^{-1}$)	Moderate RH	3.7	3.3	83	91
	High RH	5.3	4.3	62	88
20 cfm ($10\ L\cdot s^{-1}$)	Moderate RH	3.9	3.3	81	91
	High RH	4.8	3.4	74	92
Twelve Occupants					
5 cfm ($2.5\ L\cdot s^{-1}$)	Moderate RH	5.7	2.7	57	94
	High RH	5.4	4.1	59	88
10 cfm ($5\ L\cdot s^{-1}$)	Moderate RH	3.3	3.0	82	97
	High RH	6.1	4.1	48	74
15 cfm ($7.5\ L\cdot s^{-1}$)	Moderate RH	4.2	3.4	76	90
	High RH	4.6	3.5	80	81
20 cfm ($10\ L\cdot s^{-1}$)	Moderate RH	4.1	3.1	84	94
	High RH	3.8	3.3	95	97

*Ventilation rate per occupant

**Judgments came from at least 48 different persons in conditions of moderate humidity and at least 20 different persons in conditions of high humidity. Average standard error equalled 0.34 for moderate humidity and 0.55 for high humidity.

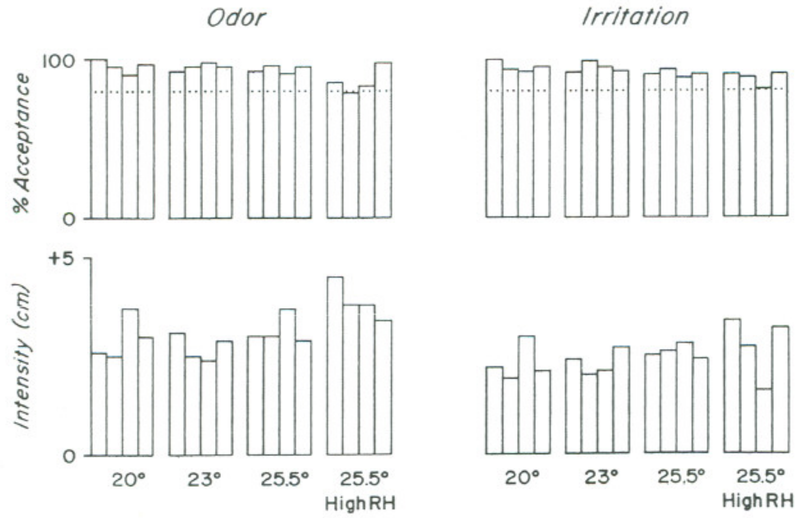


Fig. 15. Showing how occupants judged the magnitude and acceptability of the chemical attributes of the atmosphere after one hour of occupancy. Within each group of four bars, ventilation rate varies from 5 cfm (2.5 $L \cdot s^{-1}$) on the left to 20 cfm (10 $L \cdot s^{-1}$) on the right. Dotted line is plotted at 80% acceptance.

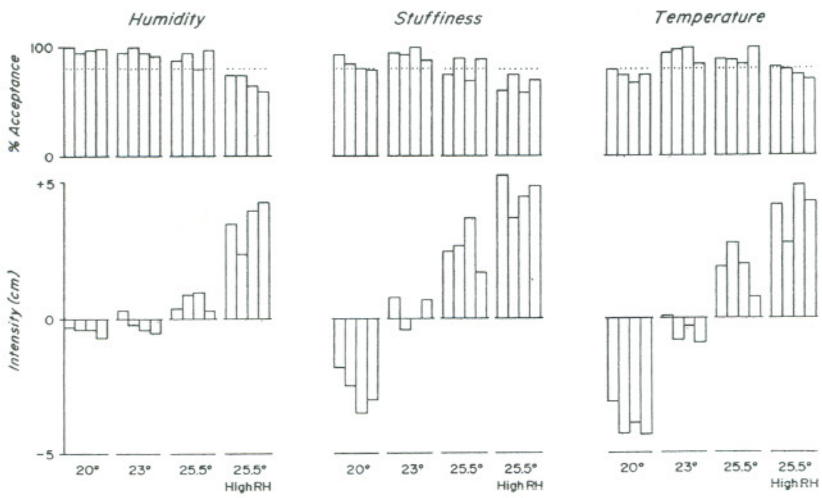


Fig. 16. Showing how occupants judged the magnitude and acceptability of three attributes after one hour of occupancy. Plotted above each of the environmental conditions denoted on the abscissa are four bars to represent (from left to right) the ventilation rates of 5, 10, 15, and 20 cfm (2.5 to 10 $L \cdot s^{-1}$) per occupant, respectively. In the case of humidity, positive values of intensity represent humid and negative values dry. In the case of stuffiness, positive values represent stuffy and negative values drafty. In the case of temperature, positive values represent warm and negative values cold. Dotted lines in the upper portion represent 80% acceptance.

When occupants expressed dissatisfaction with one or another aspect of the environment, they focused on thermal attributes. Figure 16 makes this point. If we chose a criterion of 80% acceptability, a value used in the thermal comfort standard of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), we would conclude that the environments at 20C (too cold) and at 25.5C with high humidity (too hot) failed to meet the thermal criterion. Using the same criterion of 80%, we would conclude that only the hot and humid environment failed categorically to meet the criteria for humidity (too humid) and stuffiness (too stuffy).

DISCUSSION

This investigation suggests that low ventilation rates will meet surprisingly high acceptance even under crowded conditions of sedentary occupancy. As little as 5 cfm (2.5 $L \cdot s^{-1}$) per occupant may be acceptable to three-quarters of visitors, though a rate between 5 and 10 cfm (2.5 and 5 $L \cdot s^{-1}$) 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 cu.ft. (14 m^3). Figure 17 shows how a recommendation of 7.5 cfm (3.8 $L \cdot s^{-1}$) per occupant fits with Yaglou's curve.

As mentioned earlier, Yaglou considered the possibility that inefficient mixing might account in part for the nonlinear course of the function for ventilation requirements. Poor mixing may also occur in actual buildings, a matter that deserves attention as a possible cause of energy waste. Yaglou (5) also considered the possibility that he had placed mistaken emphasis on occupancy odor:

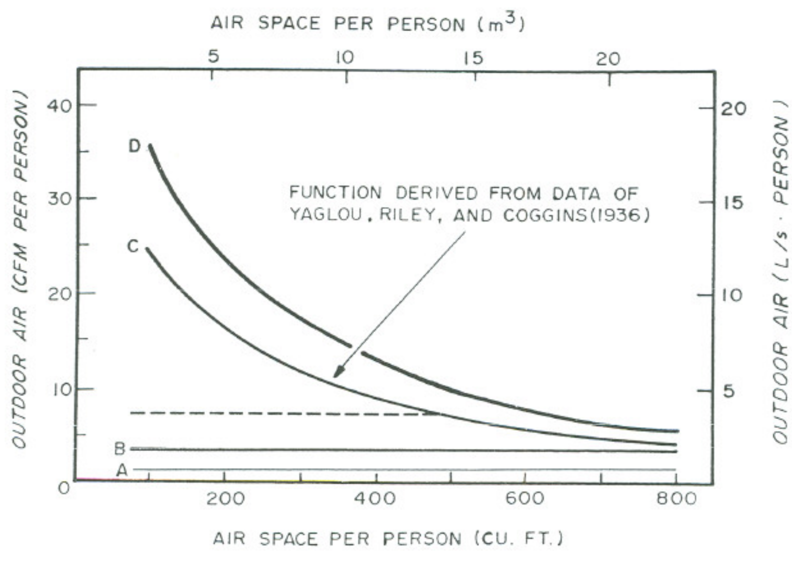


Fig. 17. Showing how a recommendation of 7.5 cfm (3.8 $L \cdot s^{-1}$) [dashed line], for crowded occupancy would fit into the pattern of constraints derived from Yaglou, Riley, and Coggins's (3) results and from requirements for oxygen (curve A) and for control of carbon dioxide (curve B). See Fig. 1.

Heretofore body odor in the air of occupied rooms was regarded as a more or less stable entity, and the problem of odor control was thought to be mainly one of plain dilution with clean outside air. Evidence obtained during the past two years does not support this view, but indicates that body odors are very unstable, tending to disappear rapidly with time, much faster than most odors with which the ventilating engineer is confronted in public buildings. [p. 423]

Although we gave no quantitative attention to this particular matter, our own personal observations fail to corroborate Yaglou's observation about the instability of occupancy odor. Whereas Yaglou claimed that this odor declined to near-threshold levels within minutes after occupants vacated an unventilated chamber, we have noticed informally that occupancy odor will linger noticeably for more than a half hour. This too deserves more thorough scrutiny both in the lab and in actual field conditions. Irrespective of whether it is stable or unstable; occupancy odor has consistently emerged as one of the three most notable indoor odor contaminants and it therefore merits careful attention (12).

Recently, Duffee et al. (13) confirmed the importance of occupancy odor in field experiments in nonsmoking areas. Using methodology very similar to that used here, these investigators measured an average odor level of 2.7 in a variety of spaces (classrooms, hospital rooms, nurses station). Visitors assessed acceptability at 75%. This degree of acceptance falls 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 real world situations.

In both Duffee's study and ours, occupancy odor was found to be quite mild. To illustrate the comparative mildness of occupancy odor, we plot in Fig. 18 how odor varied when four nonsmoking persons occupied the chamber for an hour and when four smokers occupied the chamber for 2 1/4 hrs and smoked one cigarette each during a 1-hr period. The level of intensity achieved with this smoking rate of only one cigarette per 15 min is rather remarkable. It surpasses anything seen in the study of occupancy odor. The next section illustrates the substantial intensity, discomfort, and possible health risk achievable under conditions of smoking, even with generous ventilation.

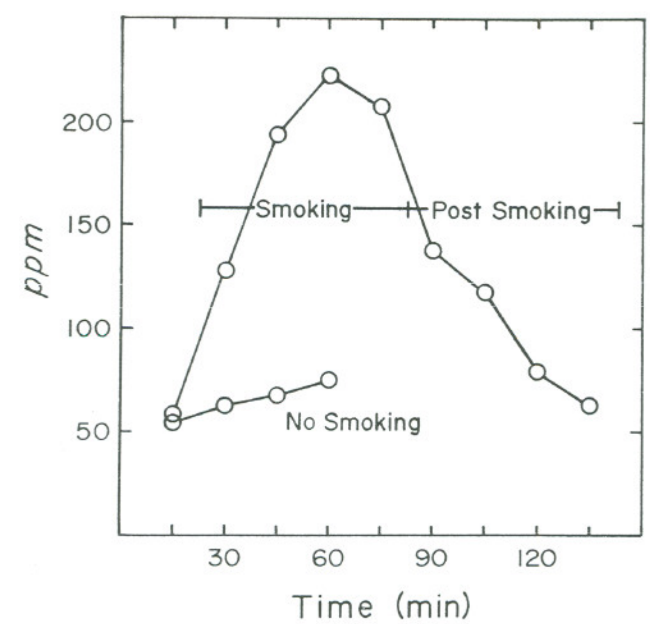


Fig. 18. Showing the odor generated by four nonsmoking occupants and by four occupants who smoked one cigarette each during one hour. The ordinate represents ppm of butanol matched to occupancy odor or tobacco smoke odor. Ventilation rate equalled 10 cfm ($5\ L \cdot s^{-1}$) per occupant.

PART 2: TOBACCO SMOKE ODOR

INTRODUCTION

Roughly one-third of the adults in the United States smoke cigarettes (14). An average smoker consumes about two cigarettes per hour during those times of day when other activities, such as eating and bathing, do not preclude smoking (15). Each cigarette emits more than a thousand chemical constituents and, among the brands of 1980, up to about 50 mg of particulate matter (16). The nature and magnitude of this complex spectrum of emissions will vary from one brand of cigarettes to another. It will also vary from smoker to smoker depending on such factors as the frequency of puffing and depth of the smoker's inhalation.

When discharged into the air of an occupied room, much of the aerosol from a cigarette deposits itself on surfaces in the room and on the bodies and in the airways of both smoker and accompanying nonsmokers. Deposition in the airways may lead to irritation and may pose a health hazard, even for the passive (i.e., unintentional) smoker (17).

After deposition on surfaces, the material from cigarettes has the general name tar to represent its dark color and sticky constituency. Tar adsorbs strongly to surfaces, but its volatile constituents continue to discharge themselves into the atmosphere long after the tar has deposited itself. A room formerly occupied by smokers may seem objectionable to the nose even hours after the smokers have left (18). For these various reasons, both the public health specialist and the ventilating engineer view tobacco smoke as the most troublesome indoor contaminant. Despite the prevalence and severity of tobacco smoke as a nuisance, ventilation requirements for it have received scant attention (19, 20). Studies of the matter have led to disparate recommendations, a frustrating situation in view of the small number of such efforts. For instance, Yaglou (21) concluded that 40 cfm (17.5 $L \cdot s^{-1}$) per smoker would suffice even when the rate of smoking equalled as much as 8 cigarettes per hour for each smoking occupant. Kerka and Humphreys (22), on the other hand, presented evidence that more than 300 cfm (150 $L \cdot s^{-1}$) per cigarette would be necessary to control odor to the criterion level of perceived magnitude previously set by Yaglou.

Subjective determinants of annoyance will play some role in the outcome of any psychophysical investigation of ventilation requirements for tobacco smoke. Even technically sound and thorough explorations will eventually become obsolete because of the changing nature of the product and changing attitudes about the privileges and responsibilities of smoker and nonsmoker. The cigarette of 1980 produces less than half the tar of the cigarette manufactured in the days of Yaglou's and Kerka and Humphrey's investigations (23). A progressive decline in what is called the delivery of cigarettes, reflected in Federal Trade Commission's ratings of tar and nicotine, has presumably led to some decline in amount of indoor pollution. This has occurred, however, at a time when nonsmokers have shown progressively less hesitation to voice annoyance over any such indoor contamination.

The experiments in the following section have a similar format to those described above for occupancy odor. That is, they take place in an experimental chamber where occupants generate contaminants and visitors judge sensory impact. The experiment may suffer from some lack of ecological validity since they take place in an unfurnished space, they require occupants to smoke at a prescribed rate rather than *ad libitum*, and they exclude nonsmokers from occupancy. Nevertheless, the experiments do permit an orderly examination of how such factors as rate of smoking, rate of ventilation, and environmental variables influence odor intensity and acceptability assessed by visitors and by smoking occupants. Furthermore, the experiments give a glimpse of the burden of particulate matter and carbon monoxide imposed on the passive smoker. In its ability to bring both psychophysical and physical measures to bear on ventilation requirements during smoking, the study has a unique character.

METHOD

Facilities

The investigation employed the methods and facilities described for the study of occupancy odor. Additional instruments relevant to the study of tobacco smoke included a carbon monoxide analyzer (Ecolyzer; Energetics Science, Inc.), a particle mass monitor (Model 3200A, Thermo-Systems, Inc.), a condensation nuclei monitor (RICH 100, Environment One), an electric aerosol size analyzer (Model 3030, Thermo-Systems, Inc.), and an optical size particle counter (Model 225 with Model 518 module, Royco Instruments).

Besides the butanol matching olfactometer used in the study of occupancy odor, the present study also employed an olfactometer designed to allow measurement of the dilution necessary to bring the odor in the air of the chamber to a just detectable level (Fig. 19). This olfactometer, called a forced-choice triangle olfactometer, generated a five-step dilution series (24). The effluent fed into the olfactometer came from 110-L Tedlar bags filled with air extracted from the chamber only moments earlier.

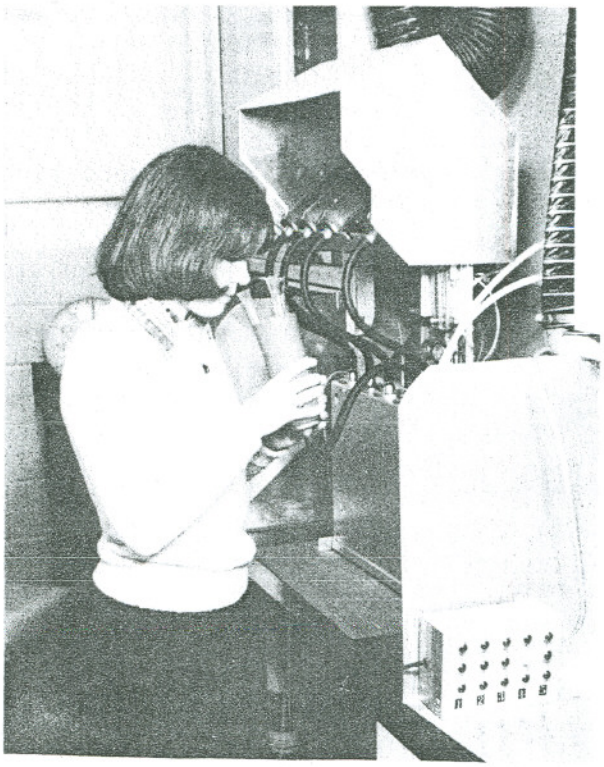


Fig. 19. Showing a participant sampling air from a forced-choice triangle olfactometer. The name derives from the requirement to choose which of three nozzles in the cup-like holder emits odorous air. Flowrate at each nozzle equals $3 L \cdot min^{-1}$. A button below each nozzle allows the person to signal a choice, registered on the box of lights at the lower right.

Subjects

Ninety-two persons participated. Median age equalled 30 yrs (range: 18 to 62). The number of sessions per participant ranged from 1 to 57 with a median of 6.

Procedure

Variables of interest included: three rates of smoking (4, 8, and 16 cigarettes per hour), six rates of ventilation (11, 16, 20, 25, 35, and 68 cfm per occupant; 5.5 to 34 $L \cdot s^{-1}$ per occupant), and four environmental conditions (20C, RH $\leq$ 50%, denoted moderate humidity; 23C, moderate humidity; 25.5C, moderate humidity; and 25.5C, RH $\geq$ 70%, denoted high humidity) (see Fig. 20 for combinations explored). 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 (pre-smoking segment), then continued with a 60-min segment of smoking, and ended with a 60-min segment of nonsmoking occupancy (post-smoking segment) for a total of 135 min. Erection of a function required judgments from approximately 25 observers. Judgments were accumulated over the course of three or four sessions (approximately 6-8 observers per session). Roughly one third of the participants smoked cigarettes regularly. When they served as visitors, smokers had the opportunity to smoke one or two cigarettes during a three-hour period of participation. The decision to allow some smoking arose from the conclusion that few smokers would participate without that opportunity. The smoking took place away from the general waiting area. Whatever influence such occasional smoking had on the visitors, the conditions presumably mimicked the customary conditions under which these persons would make judgments of indoor air quality.

Generally, four persons (all smokers) occupied the chamber during an entire 135-min period. During the smoking segment, the occupants smoked serially. A total smoking rate of four cigarettes per hour required each occupant to smoke one cigarette during one 15-min period. A rate of eight cigarettes per hour required each occupant to smoke two cigarettes (7.5 min per cigarette). A rate of 16 cigarettes per hour 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 course of the investigation, the various occupants smoked more than 30 brands. The brands ranged from < 1 mg to 20 mg per cigarette in delivery of tar and averaged approximately 14 mg. A few occupants smoked menthol cigarettes. Such cigarettes do not seem to add any distinctive odor character to the air. Furthermore, virtually all American cigarettes contain additives to fortify flavor. Menthol is only one of many additives. Each brand will therefore have a unique spectrum of organic emissions.

As in the previous experiment on occupancy odor, the visitors scaled the intensity of the reference odorant butanol by means of the numerical method of magnitude estimation at the beginning of a session. Subsequently, they assigned both numerical estimates and butanol levels to tobacco smoke odor smelled at the sniffing box. A visitor could make between four and nine such judgments per hour. At the time of the final judgments of the smoking segment and of the post-smoking segment, the visitors also marked a 13.5-cm line in order to provide another indication of intensity. They also indicated acceptability or unacceptability. For additional details, see the procedure of the experiment on occupancy odor.

Occupants of the chamber rendered their judgments only during the final moments of the 1-hr smoking segment and the 1-hr post-smoking segment. These judgments entailed marking lines to indicate odor, irritation, temperature, humidity, and stuffiness. Accompanying choices also elicited judgments of acceptability or unacceptability for each attribute.

Sessions designed to discover the dilution necessary to bring the air in the chamber to a just detectable level occurred separately from the others. In the course of 2-hr sessions, participants sought on a total of 850 occasions to detect the contaminanted (smoky) air from the chamber in samples ranging in sequence from the most dilute to undiluted. Adjacent steps in the dilution series differed by a factor of three. The participant merely had to choose the odd sample from each triad of odorous air and two blanks. When the participant reached the level of the undiluted sample, he or she then chose a level of butanol that matched the sample in intensity. Samples were generally taken during active smoking. Ventilation rate and smoking rate were varied from session to session in order to explore a wide range of intensities of undiluted samples.

RESULTS

Odor Intensity

Figure 20 shows how odor varied during 38 combinations of smoking rate, ventilation rate, and environmental conditions. The points represent medians of judgments pooled within 15-min intervals. The standard error of measurement typically equalled a quarter to a third of a butanol-scale unit.

These functions, unlike those for mere occupancy odor, span a substantial portion of the range of butanol levels. Butanol levels as high as 5 occurred routinely, whereas such levels never occurred in the study of occupancy odor. In some instances, the high judgments seemed to derive from an elevated baseline. Initial judgments of a session were sometimes only poorly related to the ventilation rate. This situation may have derived in part from the response bias discussed in connection with the investigation of occupancy odor (i.e., observers will tend to avoid a judgment of "no odor" and will instead give a token suprathreshold judgment) and in part from some lingering odors in the chamber. 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 hr apart. Even scrupulous maintenance and heavy intersession ventilation could not always eliminate lingering odors from adsorbed smoke products under such circumstances. As it turned out, these factors posed only minor 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 21 reveals that the functions for the hot, humid condition ($RH \geq 70\%$) began an average of 0.6 butanol scale units above the average for the conditions of moderate humidity ($RH \leq 50\%$). 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 an average of 0.15 scale units. Such shrinkage suggested that the influence of temperature and humidity lay in part in the magnitude of occupancy odor produced at the outset. Nevertheless, as the section on physical measures will show, the concentration of small particles increased with humidity. This outcome raises the possibility that humidity might cause a general alteration in emissions from cigarettes.

Figure 22 displays odor intensity on two linear scales, the butanol matching scale and the magnitude estimation scale, both 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

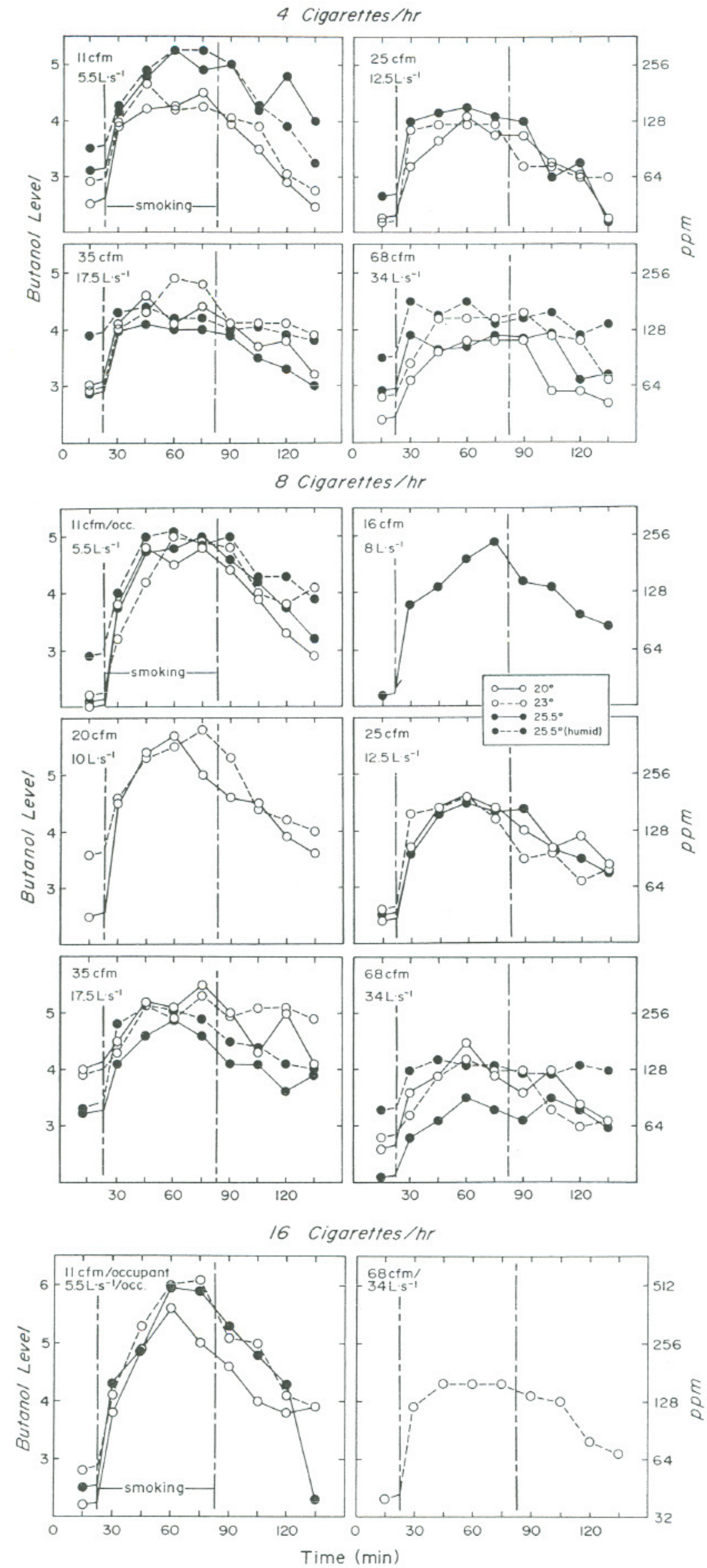
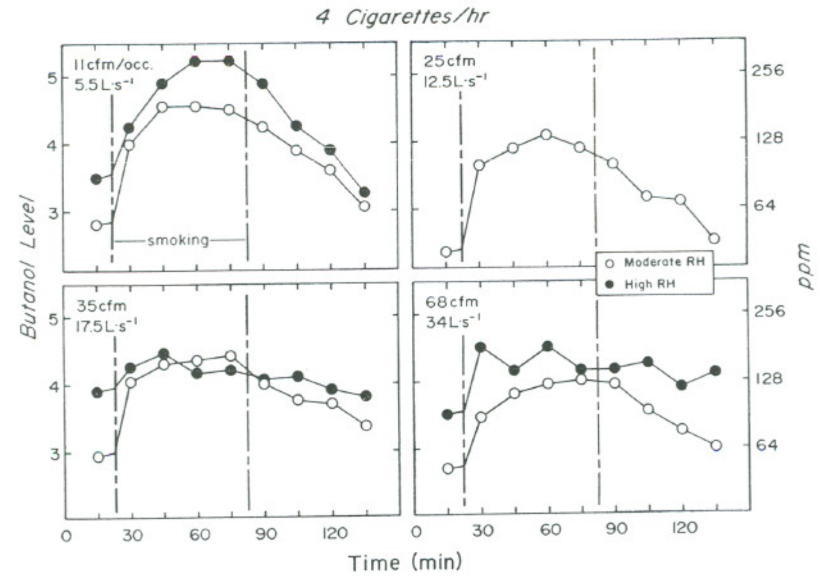


Fig. 20. Butanol matching functions obtained under 38 different conditions. Smoking began in the interval between 15 and 30 min and ended in the interval between 75 and 90 min.



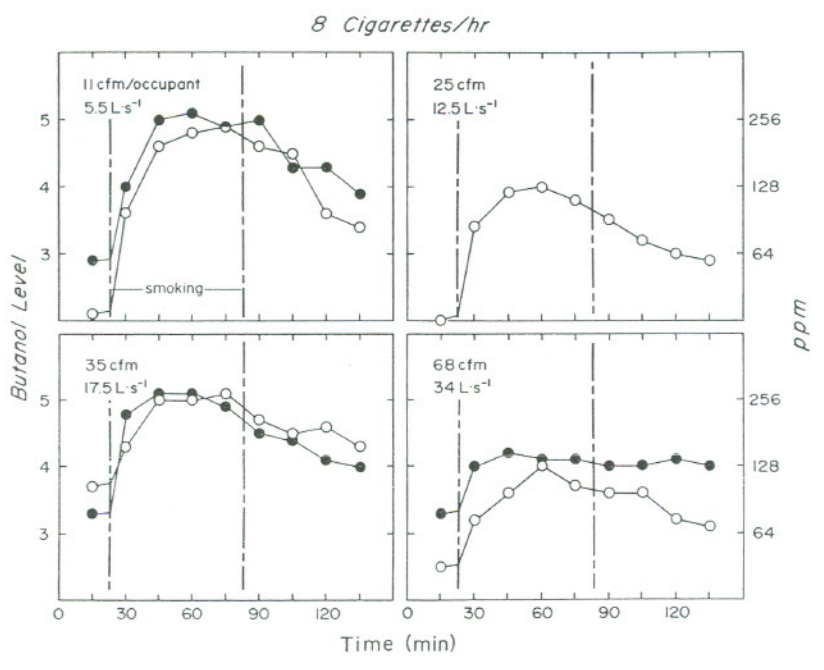


Fig. 21. Butanol matching functions averaged across conditions of moderate RH (open circles) compared with functions obtained at 25.5C and high RH (closed circles).

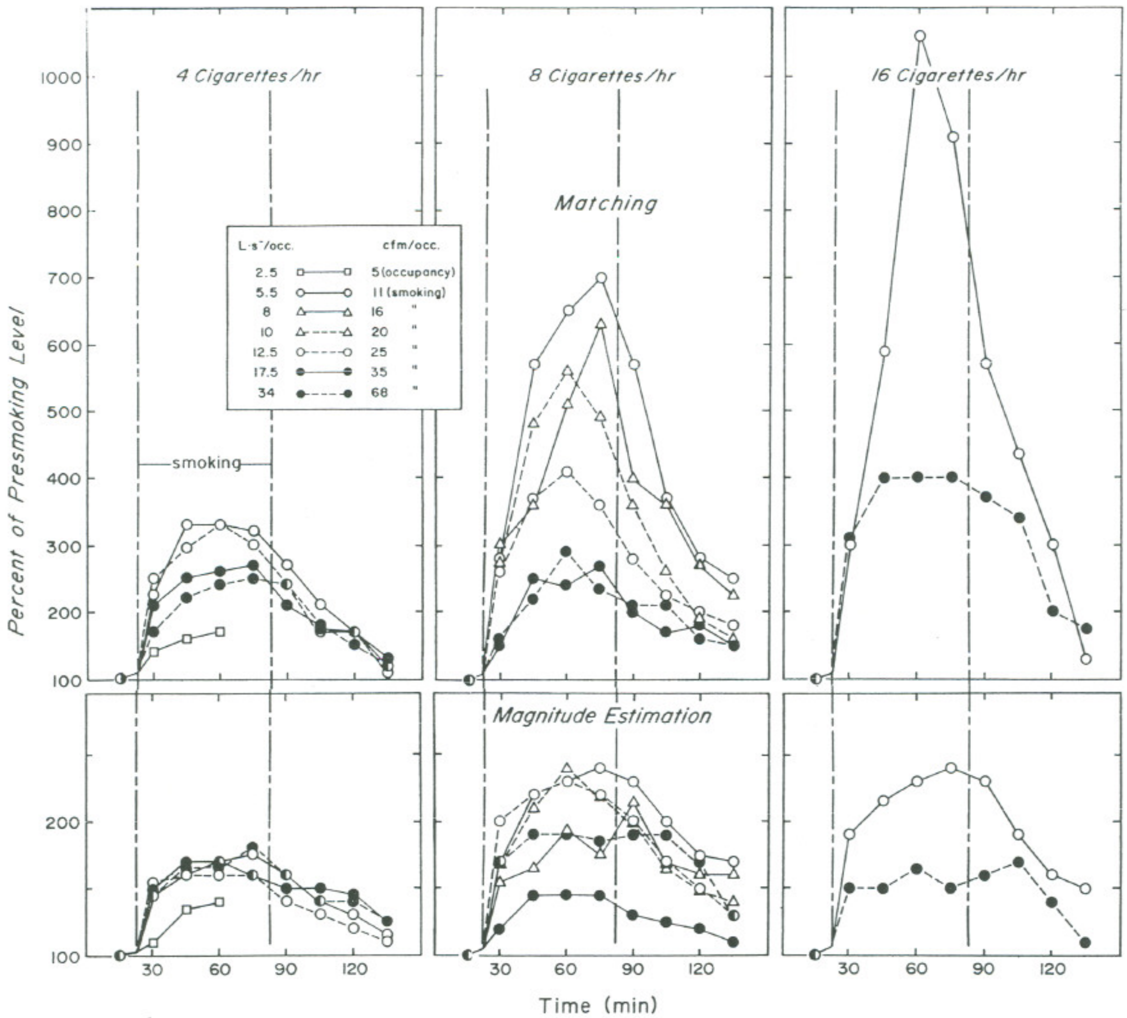


Fig. 22. Upper portion: Butanol matching functions averaged across conditions of moderate humidity and expressed as percentage of odor level achieved during 15 min of nonsmoking occupancy. Percentage was computed from ppm of butanol. Lower portion: Magnitude estimation functions derived from judgments rendered at the same time as the butanol matches that formed the functions in the upper portion.

that the high ventilation rates used to combat cigarette smoking would control occupancy odor with ease, a situation that would therefore blunt any dependence of that odor on such high rates of ventilation. Figure 22 also contains, for reference, functions that depict how magnitude of occupancy odor varied over time with the rather meager ventilation rate of only 5 cfm ($2.5\ L \cdot s^{-1}$) per occupant. Note that tobacco smoke odor exceeded occupancy odor no matter how high the ventilation rate during smoking.

The dependence of odor on rate of ventilation revealed itself more strongly in the results of butanol matching than in the results of magnitude estimation. Such a difference between the two scales reflects in part the customary compression seen in the psychophysical function relating perceived odor magnitude to odorant concentration (Fig. 23). A one-hundredfold change in butanol concentration yielded a less than tenfold change in perceived odor magnitude. As with occupancy odor, we chose to use butanol level as the primary index of intensity.

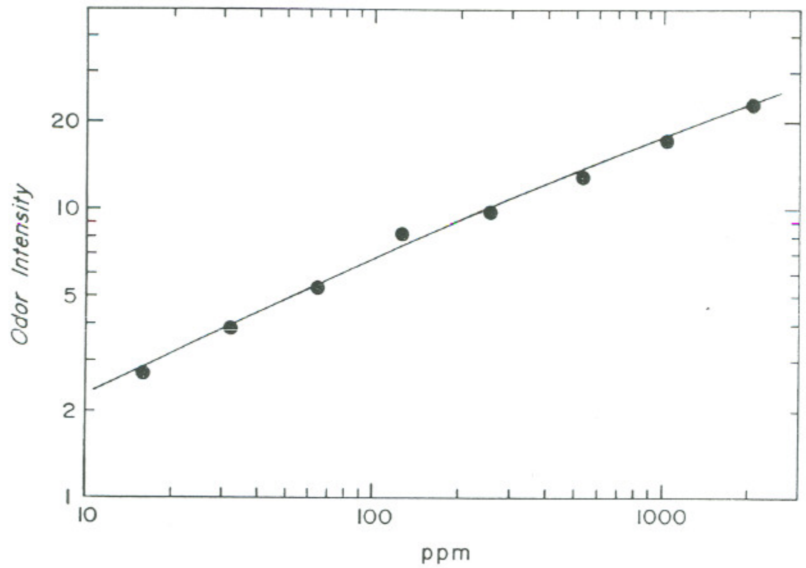


Fig. 23. Psychophysical function relating the perceived intensity of butanol to concentration. The fitted function conforms to the equation $\psi = k(\phi-\alpha)^{\beta}$ where ψ refers to perceived magnitude and ϕ to concentration. The parameter α equalled 6 ppm and the exponent β equalled 0.39. These values come very close to those obtained when visitors scaled butanol during the experiments on occupancy odor (Fig. 11).

Dependence of odor on rate of ventilation also displayed itself more strongly at 8 and 16 cigarettes than at 4 cigarettes per hour. At the low rate of smoking, ventilation rates ranging from 11 to 68 cfm (5.5 to 34 $L\cdot s^{-1}$) per occupant led to similar odor levels. The reason for this outcome becomes apparent from measurements of the physical stimulus, a matter treated more thoroughly 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 emerges 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.

Odor Acceptability

The acceptance of tobacco smoke odor as a function of intensity (Fig. 24) followed a pattern rather similar to that for occupancy odor (Fig. 14). In the present case, however, the generally high odor levels precluded 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. A criterion of 75-80% acceptance was a realistic goal for occupancy odor, but is apparently not for tobacco smoke odor. At the smoking rate of 4 cigarettes and at moderate humidity, approximately two-thirds of visitors found ventilation rates at or about 25 cfm (12.5 $L\cdot s^{-1}$) per occupant acceptable. High humidity led to higher odor intensity and substantially lower acceptability.

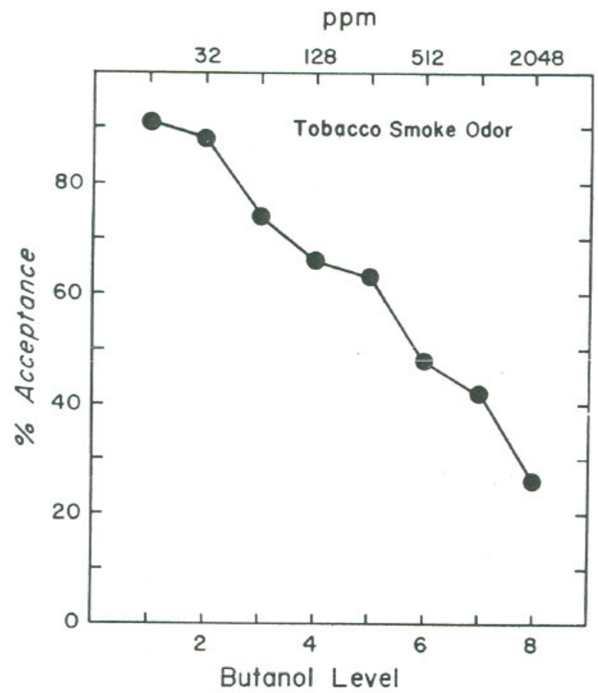


Fig. 24. Showing the relation between acceptance and intensity of tobacco smoke odor, expressed as butanol equivalent, for data gathered across all visitors and all experiments. The number of observations equalled 2357.

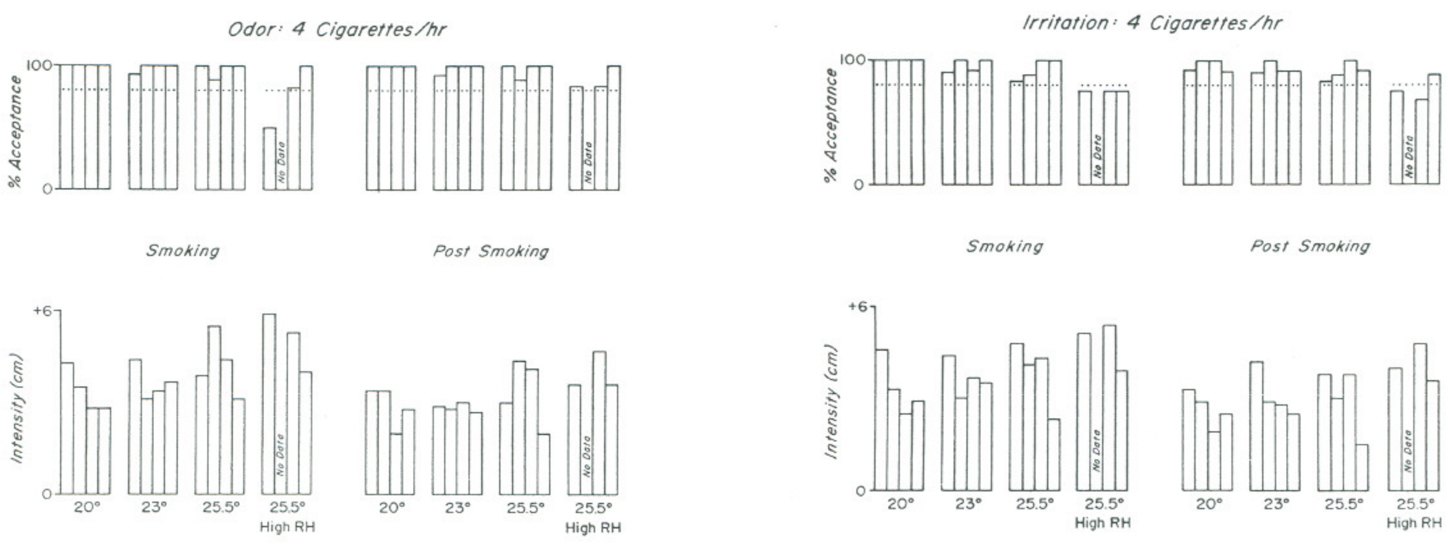


Fig. 25. Showing how occupants (smokers) rated the intensity and acceptability of odor and irritation during smoking of 4 cigarettes per hour and during post-smoking segments. In each group of 4 bars, ventilation rate varies from left to right as follows: 11 cfm (5.5 $L \cdot s^{-1}$) per occupant, 25 cfm (12.5 $L \cdot s^{-1}$), 35 cfm (17.5 $L \cdot s^{-1}$), and 68 cfm (34 $L \cdot s^{-1}$).

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.

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

*Ventilation rate per occupant.

** Judgments came from at least 21 <u>different</u> 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. 26. Showing how occupants (smokers) rated the magnitude and acceptability of humidity, stuffiness, and temperature during smoking of 4 cigarettes per hour and during post-smoking segments. In each group of 4 bars, ventilation rate varies from left to right as follows: 11 cfm (5.5 $L \cdot s^{-1}$) per occupant, 25 cfm (12.5 $L \cdot s^{-1}$), 35 cfm (17.5 $L \cdot s^{-1}$) and 68 cfm (34 $L \cdot s^{-1}$) per occupant.

Unlike the visitors, occupants (smokers themselves) found the odor of the environment generally acceptable during the period of smoking 4 cigarettes (Table 2; Fig. 25). Despite their tolerance of odor, these persons found the air unacceptably stuffy relatively often (Fig. 26).

At the smoking rate of 8 cigarettes per hour, only ventilation rates of 25 and 68 cfm (12.5 and 34 $L \cdot s^{-1}$) per occupant seemed acceptable to two-thirds or more visitors. A rate of 35 cfm (17.5 $L \cdot s^{-1}$) per occupant at moderate humidity seemed acceptable to only 51% of visitors. A disparity between odor intensity at 25 and 35 cfm (12.5 and 17.5 $L \cdot s^{-1}$) arose even before smoking began (see Fig. 20) and we know the source of the disparity. Sessions conducted at 35 cfm (17.5 $L \cdot s^{-1}$) per occupant took place in close temporal proximity with sessions conducted to reveal steady state levels of particulate matter under circumstances that included very intense smoking, up to 24 cigarettes per hour. Those experiments (see Figs. 34, 38, and 42) had no psychophysical component but led to odors that lingered over days. Dismantling and cleansing of all reachable surfaces virtually eliminated the odor. Sessions conducted at 25 cfm per occupant occurred almost immediately after cleaning.

Inclusion of both smokers and nonsmokers among the visitors permitted erection of separate acceptance functions for the two groups (Fig. 27). As might be expected, nonsmokers set more stringent criteria for acceptance than smokers. In the critical region of 65 to 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 evaporate with consideration of nonsmokers. None of the conditions in the present investigation would satisfy even two-thirds of nonsmokers.

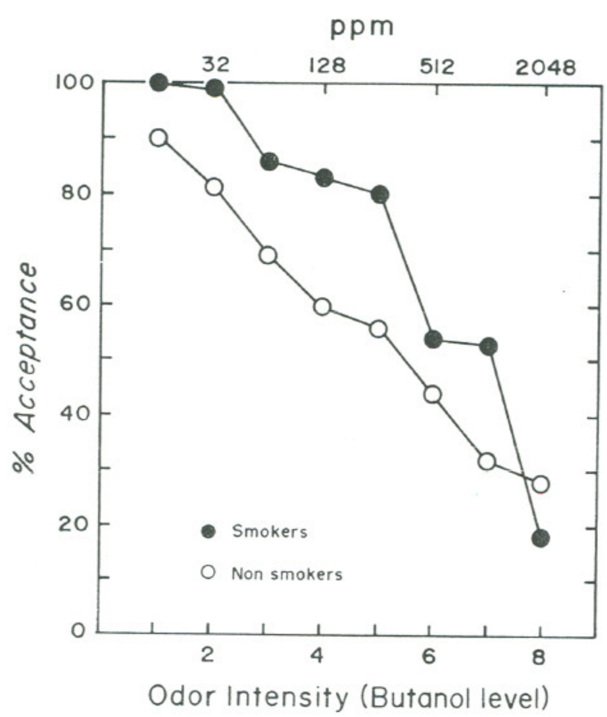


Fig. 27. Showing the relation between acceptance and intensity of tobacco smoke odor, expressed as butanol equivalent, plotted for smokers and nonsmokers separately.

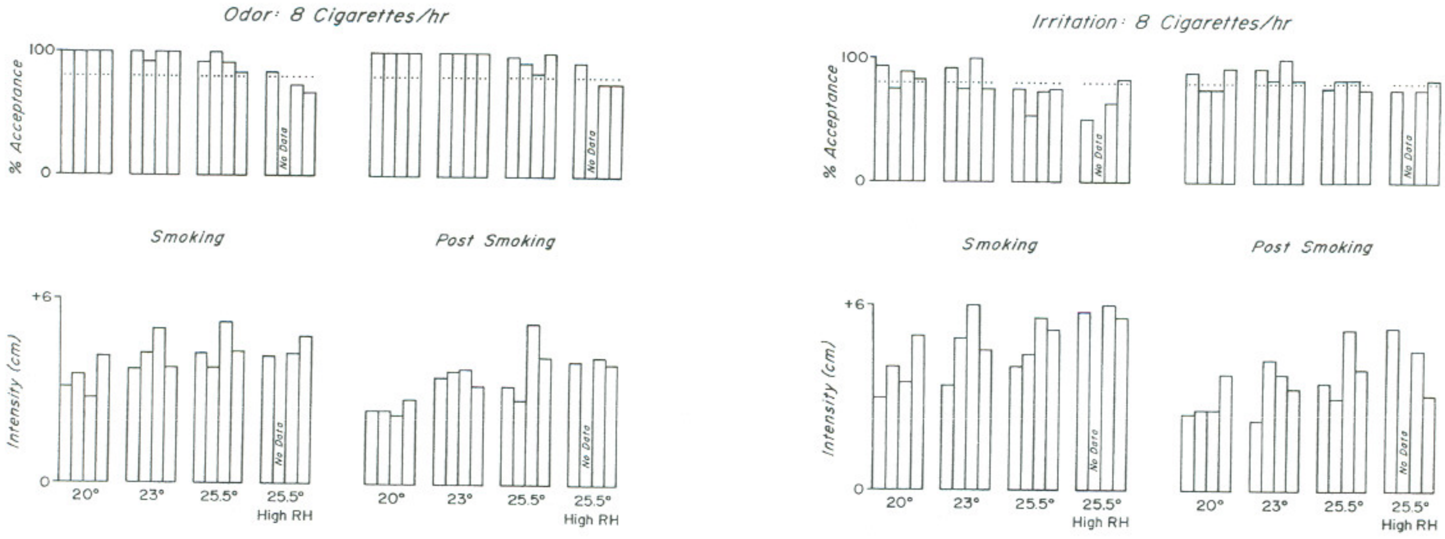


Fig. 28. Showing how occupants (smokers) rated the intensity and acceptability of odor and irritation during smoking of 8 cigarettes per hour and during post-smoking segments. For key to bars see Fig. 26.

As in the case of 4 cigarettes per hour, the occupants (unlike visitors) complained little about odor at the smoking rate of 8 cigarettes. Nevertheless, the occupants found the odor less acceptable under conditions of high temperature and humidity (Fig. 28). These persons also began to find other attributes of the environment less acceptable than had occupants during the experiments on nonsmoking occupancy (compare Fig. 29 with Fig. 16). It seemed that the presence of cigarette smoke amplified annoyance caused by other sources.

Odor Detectability

Figure 30 portrays how detectability varied with suprathreshold intensity of undiluted chamber air. The upper part of the figure contains psychometric functions (percent correct detection vs concentration) plotted without correction for the guessing probability of 1/3 in the three-alternative forced-choice task. A given function portrays the detectability data obtained from those participants who matched undiluted air from the chamber to the particular butanol level denoted at the top of the figure. The lower part of the figure shows the data corrected for chance (i.e., for guessing). Only points above chance level were included in the corrected functions. The concentrations necessary for 50% detection ("threshold" concentrations) varied monotonically with butanol level, but covered a relatively small range. One interpretation of this outcome is that the psychophysical (suprathreshold) function for tobacco smoke odor grows more rapidly with concentration than does the butanol function. Irritating properties of tobacco smoke could play a role in such possible rapid growth.

Carbon Monoxide

Figure 31 shows how carbon monoxide attributable to smoking varied with time during a smoking rate of 4 cigarettes per hour. The curves summarize 1 to 6 runs at the various ventilation rates. In these and subsequent graphs, t=0 min represents the point when smoking began and ambient concentration prior to smoking was subtracted from concentrations attained during and after smoking. The graphs display a cyclicity

Fig. 29. Showing how occupants (smokers) rated the intensity and acceptability of humidity, stuffiness, and temperature during smoking of 8 cigarettes per hour and during post-smoking segments. For key to bars see Fig. 26.

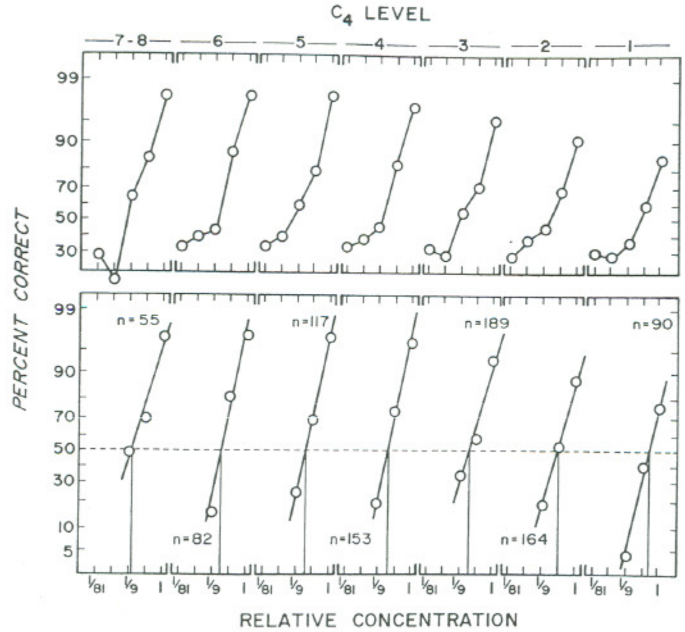


Fig. 30. Showing the detectability (percent correct) of various intensities of tobacco smoke odor. The butanol (C_4) level at the top signifies the intensity of undiluted samples from the chamber. For example, the function for level 4 shows how a sample of that intensity changed in its detectability as it was diluted with clean air to various degrees. The values of n in the lower portion stand for the number of participant-sessions that comprise a function. Lines that intersect the abscissa depict "threshold" concentrations expressed relative to undiluted chamber air (concentration of 1.0).

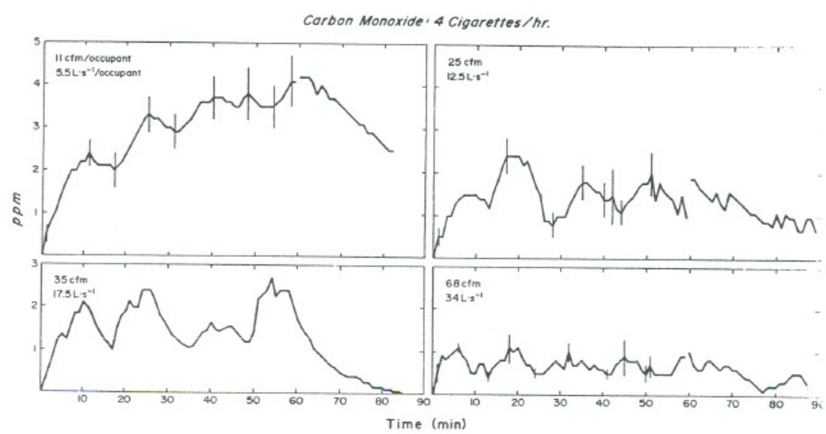


Fig. 31. Variation of carbon monoxide during smoking of 4 cigarettes (t=0 to 60 min) and during the post-smoking segment. Number of runs included in the various panels was as follows: 6 runs at 11 cfm ($5.5\ L\cdot s^{-1}$) per occupant, 4 at 25 cfm ($12.5\ L\cdot s^{-1}$), 1 at 35 cfm ($17.5\ L\cdot s^{-1}$) and 5 at 68 cfm ($34\ L\cdot s^{-1}$). In this and in subsequent graphs, curves derived from more than 3 runs are accompanied by representative standard errors.

associated with the regularity of the smoking, i.e., one cigarette every 15 min. During any individual run, the peaks stand 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 (see curve for 35 cfm [17.5 $L \cdot s^{-1}$] which came from a single run). Standard errors, depicted on the graphs, reveal the session-to-session variability that, in a manner of speaking, confronted the psychophysical observers.

The point in time when smoking actually ended varied slightly from session to session. In order to capture the true decline after smoking, we sought to decide the moment when smoking ceased and then to average values that fell into register with respect to that moment. This effort to place the declines in register accounts for discontinuities seen in some graphs in the vicinity of t=60 min.

At the smoking rate of 4 cigarettes per hour and a ventilation rate of 11 cfm (5.5 $L \cdot s^{-1}$) 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 unhealthful levels. The national ambient air quality standard for this pollutant limits its concentration to 9 ppm averaged over an 8-hr period and 35 ppm averaged over a 1-hr period.

Ventilation rates of at least 25 cfm (12.5 $L \cdot s^{-1}$) per occupant controlled carbon monoxide with relative ease. Interestingly, the concentrations attained at 25 cfm (12.5 $L \cdot s^{-1}$) roughly equalled those attained at 35 cfm (17.5 $L \cdot s^{-1}$). This presumably occurred through chance factors, rather than through any factors associated with maintenance of the chamber. A similar phenomenon seems to have occurred during smoking rates of 8 cigarettes per hour (see Fig. 32); average concentrations

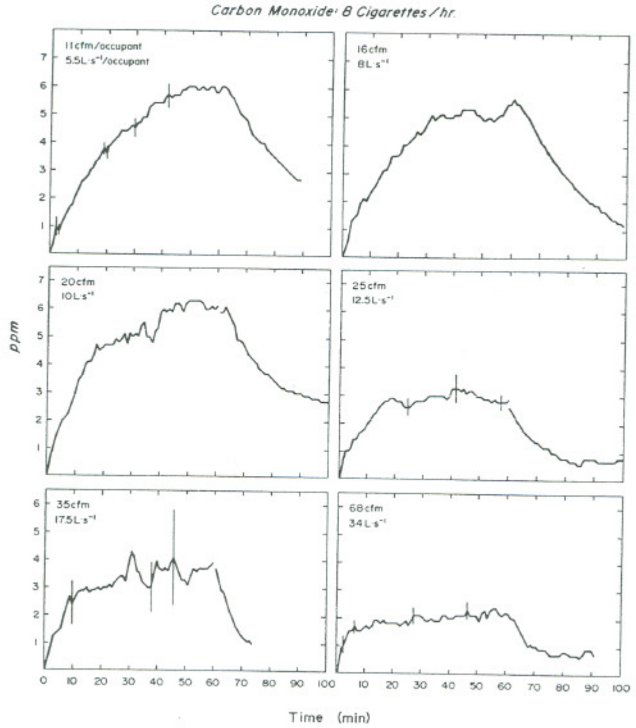


Fig. 32. Variation of carbon monoxide during smoking of 8 cigarettes per hour and during the post-smoking segment. Number of runs per condition were as follows: 11 runs at 11 cfm (5.5 $L \cdot s^{-1}$), 3 at 16 cfm (8 $L \cdot s^{-1}$), 3 at 20 cfm (10 $L \cdot s^{-1}$), 8 at 25 cfm (12.5 $L \cdot s^{-1}$), 5 at 35 cfm (17.5 $L \cdot s^{-1}$), and 8 at 68 cfm (34 $L \cdot s^{-1}$).

achieved during a ventilation rate of 35 cfm (17.5 $L \cdot s^{-1}$) per occupant actually exceeded those attained during rates of 25 cfm (12.5 $L \cdot s^{-1}$) per occupant. Concentrations attained at 35 cfm (17.5 $L \cdot s^{-1}$) also display very high variability. These unanticipated outcomes have instructional value insofar as they reveal some of the complexity and variation that must characterize actual field situations. The particular disparity highlighted here also shows up in the records for other contaminants shown below.

At smoking rates of 8 and 16 cigarettes per hour, individual cigarettes did not show up as discernible peaks in the average records (Figs. 32 and 33). As in the case of four cigarettes per hour, the curves obviously continued to climb throughout the period of smoking whenever the ventilation rate fell below 25 cfm (12.5 $L \cdot s^{-1}$). Even rates above 25 cfm (12.5 $L \cdot s^{-1}$) exhibit some inability to eliminate growth by the end of the 1-hr 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.

The data from Figs. 31 through 33 came from a mixture of cigarettes chosen, in effect, by the smokers themselves. The data in Fig. 34 came from smoking Marlboro (85-mm length, 18 mg tar), the most commonly smoked cigarette in the world. The points represent steady-state or,in the case of 4 cigarettes per hour, quasi-steady-state levels achieved during bouts of smoking that lasted long enough to achieve steady state. The data obtained from smoking Marlboro agreed rather well with those obtained from smoking a variety of brands.

Particulate Matter

Total suspended particulate (TSP) mass concentration followed a pattern much like that of carbon monoxide: 1) cyclicity at four cigarettes per hour (Fig. 35), 2) a time-averaged rise throughout the smoking segment at ventilation rates less than 25 cfm (12.5 $L \cdot s^{-1}$) per occupant for all three rates of smoking (Figs. 35-37), and 3) poor resolution between 25 and 35 cfm (12.5 and 17.5 $L \cdot s^{-1}$) per occupant (Figs. 35 and 36). TSP differed from carbon monoxide in the relative severity of the levels achieved. Unlike the graphs for carbon monoxide, the graphs for TSP include the pre-smoking baseline. This averaged less than 35 $\mu g/m^3$. In virtually all instances, TSP concentrations exceeded those deemed acceptable by one or another criterion. Figure 38, like Fig. 34, displays levels achieved during smoking of Marlboro. As levels A-C on the ordinate reveal, all combinations of smoking and ventilation exceeded the annual average concentration limits (national ambient air quality standards) set to protect welfare (A, 60 $\mu g/m^3$) and health (B, 75 $\mu g/m^3$), whereas most combinations exceeded the 24-hr average concentration limit not to be exceeded more than once a year (C, 260 $\mu g/m^3$). Other relevant standards for particulate concentration include the emergency level (D, 875 $\mu g/m^3$) and the level for significant harm (E, 1000 $\mu g/m^3$).

The particles, as measured with the electric aerosol size analyzer and optical size particle counter, fell almost entirely (> 95% of mass) in the size range 0.1 to 2 μm in diameter, with a mass median diameter of approximately 0.4 μm. The number of particles less than 0.1 μm, assessed by the condensation nuclei counter, fell below the average ambient concentration found in New York City in winter. Figures 39 through 41 show the actual variation of concentration of condensation nuclei during smoking and Fig. 42 shows the levels achieved from smoking Marlboro. These figures exclude the baseline of about 20,000 particles per cm^3 typically found in the chamber. The internal pattern of results falls in register with that found with the total suspended particulate mass and carbon monoxide.

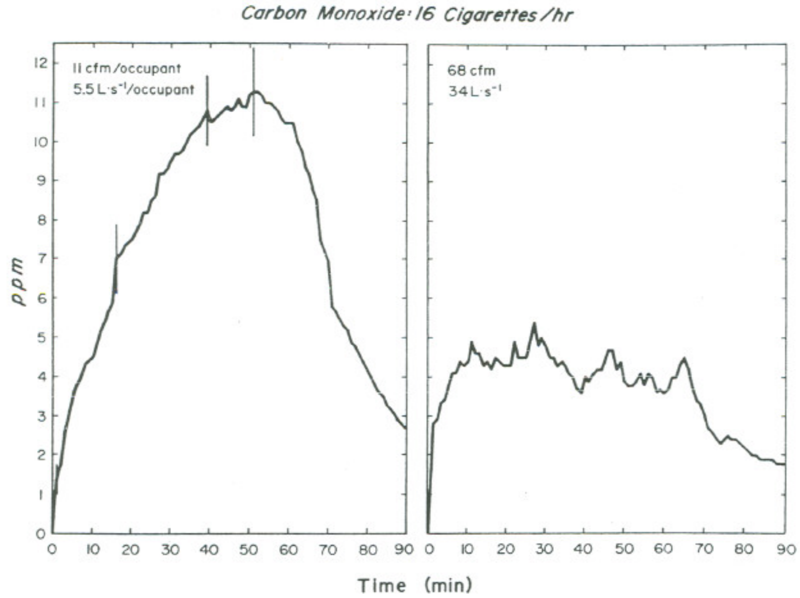


Fig. 33. Variation of carbon monoxide during smoking of 16 cigarettes per hour and during the post-smoking segment. Number of runs per condition was as follows: 5 runs at 11 cfm (5.5 $L{\cdot}s^{-1}$) and 1 at 68 cfm (34 $L{\cdot}s^{-1}$).

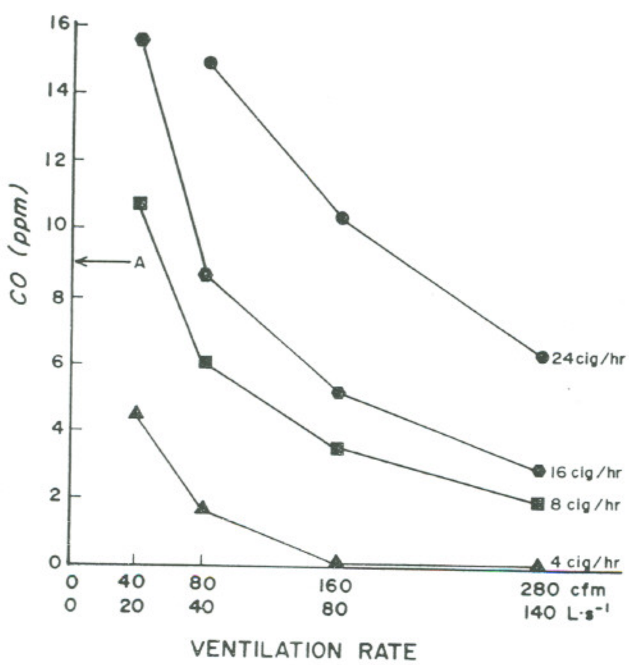


Fig. 34. Showing how carbon monoxide varied with total ventilation rate at various rates of smoking. The data represent steady-state levels. The level designated A represents the national ambient air quality standard of 9 ppm (8-hr running average). The standard for 1-hr average equals 35 ppm, not shown here.

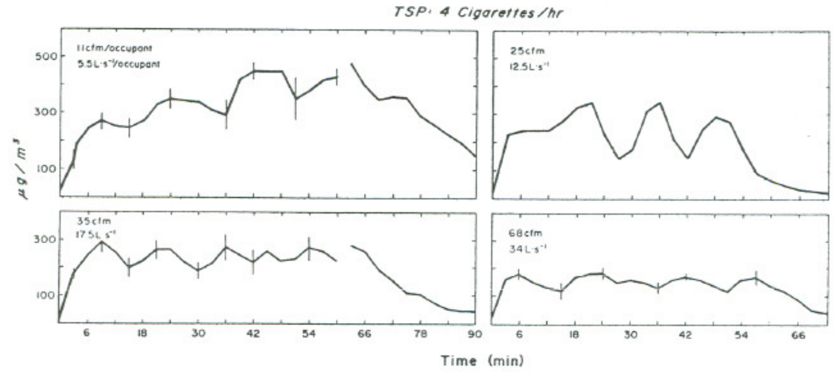


Fig. 35. Variation of particulate mass concentration during smoking of 4 cigarettes per hour and during the post-smoking segment. Number of runs per condition was as follows: 8 runs at 11 cfm (5.5 L·s^{-1}), 3 at 25 cfm (12.5 L·s^{-1}), 9 at 35 cfm (17.5 L·s^{-1}), and 8 at 68 cfm (34 L·s^{-1}).

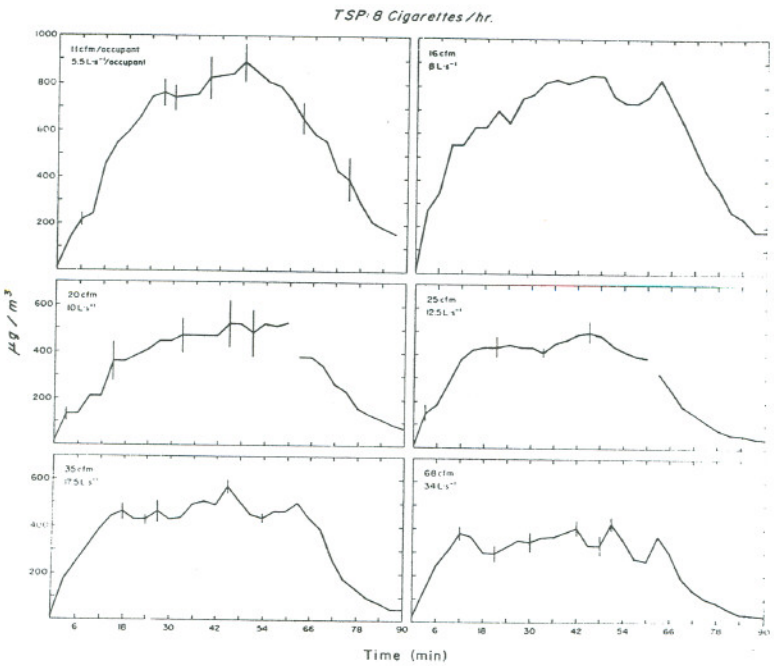


Fig. 36. Variation of particulate mass concentration during smoking of 8 cigarettes per hour and during the post-smoking segment. Number of runs per condition was as follows: 9 runs at 11 cfm (5.5 L·s^{-1}), 3 at 16 cfm (8 L·s^{-1}), 4 at 20 cfm (10 L·s^{-1}), 4 at 25 cfm (12.5 L·s^{-1}), 7 at 35 cfm (17.5 L·s^{-1}), and 8 at 68 cfm (34 L·s^{-1}).

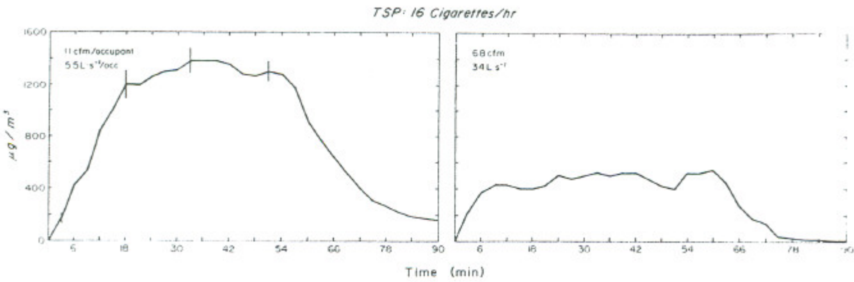


Fig. 37. Variation of particulate mass concentration during smoking of 16 cigarettes per hour and during the post-smoking segment. Number of runs per condition was as follows: 5 runs at 11 cfm (5.5 $L \cdot s^{-1}$) and 2 at 68 cfm (34 $L \cdot s^{-1}$).

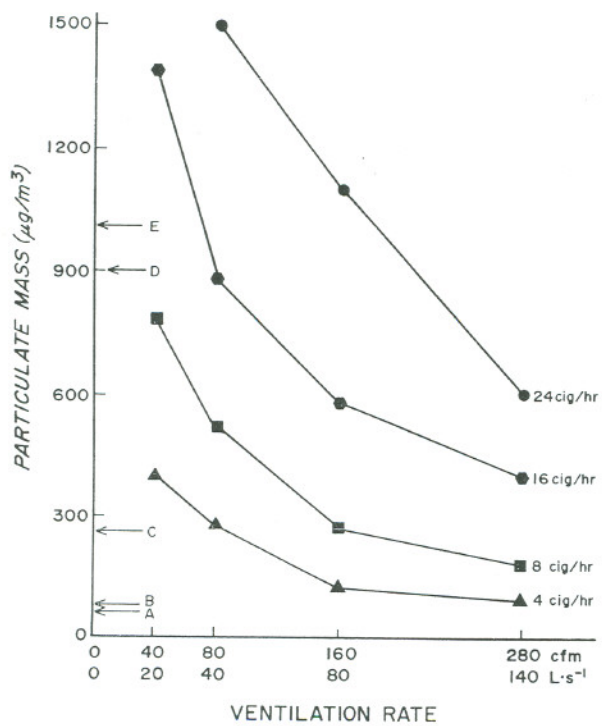


Fig. 38. Showing how particulate mass concentration varied with total ventilation rate at various rates of smoking. The data represent steady-state levels. The levels denoted A-E represent the following: A, secondary ambient air quality standard (annual arithmetic average) set to protect public welfare; B, primary ambient air quality standard set to protect public health; C, 24-hr average level set to protect public health and not to be exceeded more than once a year; D, 24-hr average concentration for air pollution emergency; and E, 24-hr average concentration for significant harm.

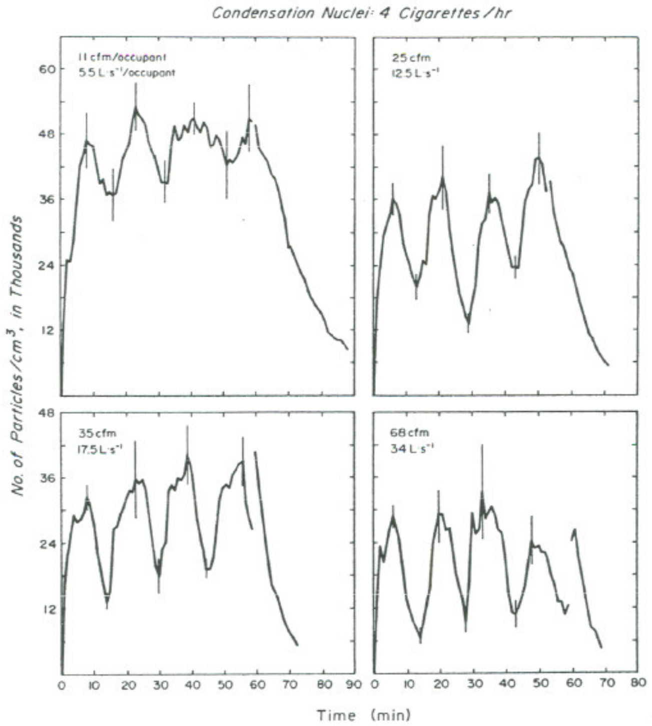


Fig. 39. Variation in condensation nuclei concentration during smoking of 4 cigarettes per hour and during the post-smoking segment. Number of runs per condition was as follows: 8 runs at 11 cfm (5.5 $L \cdot s^{-1}$), 4 at 25 cfm (12.5 $L \cdot s^{-1}$), 8 at 35 cfm (17.5 $L \cdot s^{-1}$), and 8 at 68 cfm (34 $L \cdot s^{-1}$).

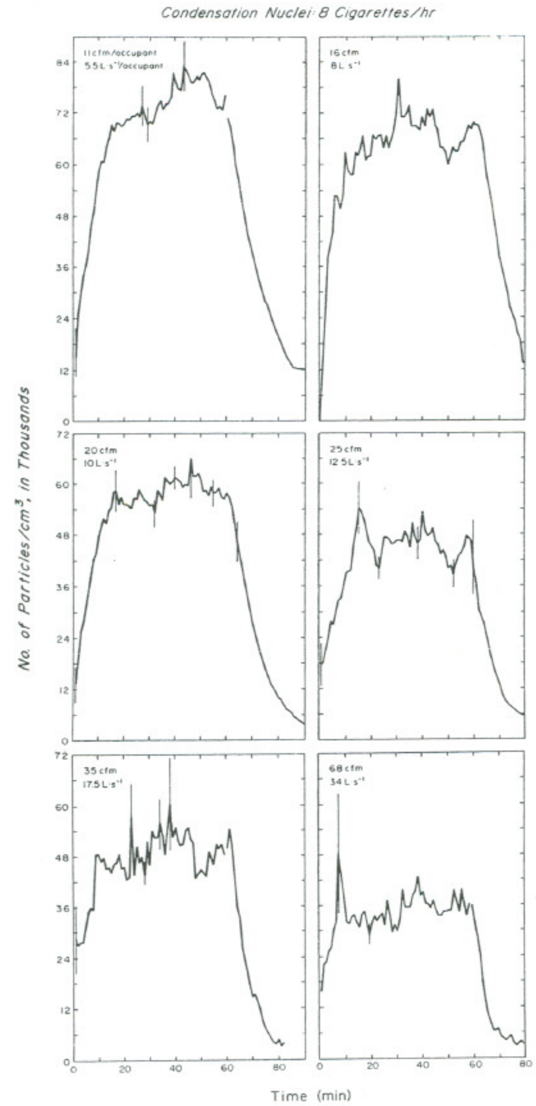


Fig. 40. Variation in condensation nuclei concentration during smoking of 8 cigarettes per hour and during the post-smoking segment. Number of runs per condition was as follows: 1 run at 11 cfm (5.5 $L \cdot s^{-1}$), 3 at 16 cfm (8 $L \cdot s^{-1}$), 6 at 20 cfm (10 $L \cdot s^{-1}$), 8 at 25 cfm (12.5 $L \cdot s^{-1}$), 7 at 35 cfm (17.5 $L \cdot s^{-1}$), and 9 at 68 cfm (34 $L \cdot s^{-1}$).

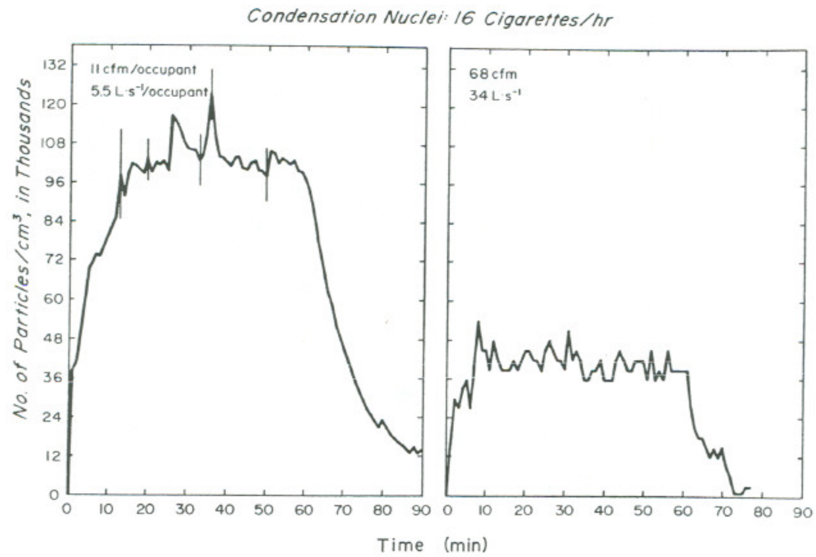


Fig. 41. Variation in condensation nuclei concentration during smoking of 16 cigarettes per hour and during the post-smoking segment. Number of runs per condition was as follows: 5 runs at 11 cfm (5.5 $L\cdot s^{-1}$) and 3 at 68 cfm (34 $L\cdot s^{-1}$).

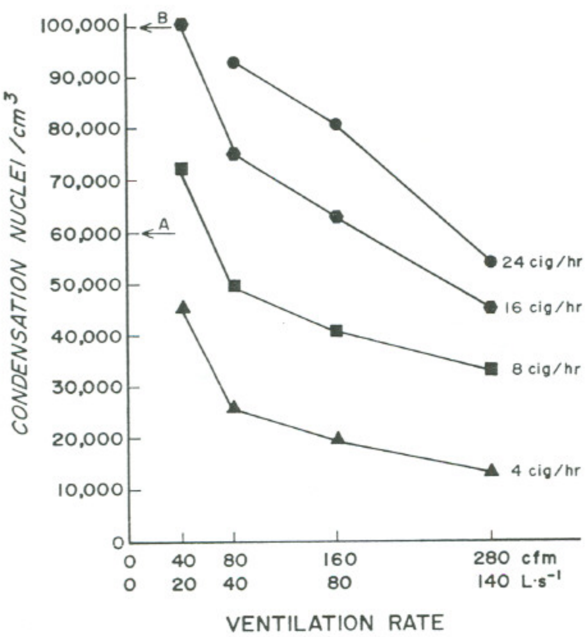


Fig. 42. Showing how condensation nuclei concentration varied with total ventilation rate at various rates of smoking. The data represent steady-state levels. The levels A and B represent, respectively, a typical ambient concentration in New York City during summer and a typical concentration in New York City during winter.

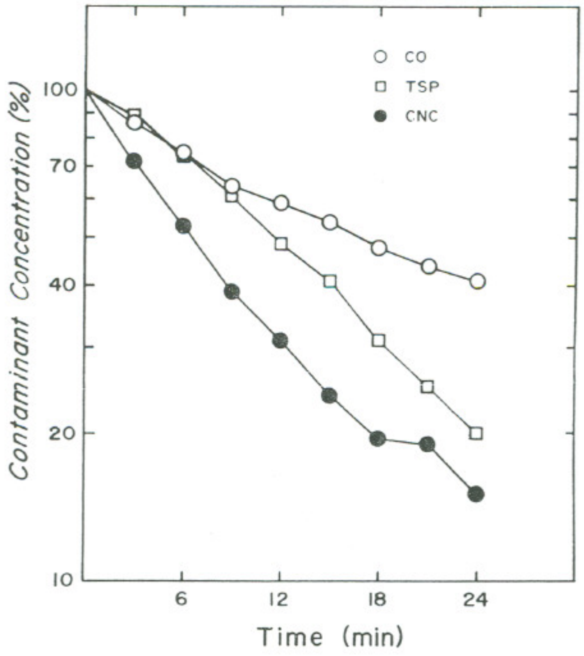


Fig. 43. Showing the relative rates of decay of carbon monoxide concentration (CO), particulate mass concentration (TSP), and condensation nuclei concentration (CNC) during the post-smoking segments. The results are averages taken across many combinations of smoking and ventilation rates.

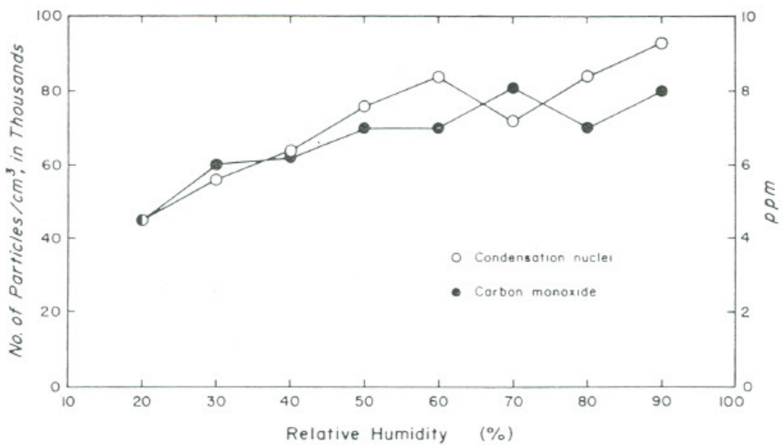


Fig. 44. Showing how condensation nuclei (left ordinate, no. of particles per cm^3) and carbon monoxide (right ordinate, ppm) varied with relative humidity during continuous smoking of one cigarette at a time (Marlboro) at a dry bulb temperature of 23C and a total ventilation rate of 40 cfm (20 $L \cdot s^{-1}$).

Interrelations among factors followed some expected and some unexpected paths. For instance, particles predictably decayed more rapidly than carbon monoxide from the moment when smoking ceased (Fig. 43). Whereas carbon monoxide could escape from the air in the chamber only via dilution and flushing, particles could escape via the additional route of diffusion onto surfaces (25). The high recirculation rate of 2000 cfm (1000 $L \cdot s^{-1}$) undoubtedly facilitated existing opportunities for a given particle to diffuse and settle onto surfaces.

Unexpectedly, the concentration of small particles increased with humidity. On the average, the increase equalled about 20% from conditions of moderate humidity ($\leq$ 50%) to those of high humidity ($\geq$ 70%). Concentration of carbon monoxide showed no similar increase during regular smoking runs. Nevertheless, both contaminants increased in concentration under conditions wherein individual cigarettes (always Marlboro) were smoked one at a time (Fig. 44). The covariation of the two contaminants, one gaseous and one particulate, suggests that actual emissions increased with humidity rather than the alternative possibility that emissions remained constant but that small particles remained in the air longer at high humidities.

DISCUSSION

Ventilation requirements for smoking can be based on various indices, e.g., odor perceived by visitors (19), irritation experienced by nonsmoking occupants (26), haze (smokiness) (27), or criterion concentrations of contaminants (28, 29). 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 the condition of 8 cigarettes per hour and 68 cfm (34 $L \cdot s^{-1}$) per occupant, which led to 90% acceptance by the visitors who actually participated in those runs, would probably fail to meet the criterion frequently. That condition led to a butanol scale level of 3.6 (Fig. 21), which would meet, on the average, only 70% acceptance according to the composite function derived from both smokers and nonsmokers (Fig. 24) and only 63% acceptance according to the function derived from nonsmokers alone (Fig. 27).

The relation between percent acceptance and odor intensity in the experiments on smoking came out much the same as in the experiments on nonsmoking occupancy. Figures 45 and 46 depict 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.

The standard entitled "Ventilation for Acceptable Indoor Air Quality" of the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) suggests that a subjective evaluation of the quality of the air in a room should elicit judgments of acceptability or objectionability from a panel of untrained observers (visitors). Subjective criteria for acceptability are probably quite labile and can undoubtedly be manipulated readily even unintentionally. Judgments of intensity seem intuitively less subject to manipulation. A strong relation between percent acceptance and odor intensity in the relatively neutral context of a model environment such as our chamber would suggest that intensity might replace acceptability as the critical judgment in the ASHRAE scheme. This conclusion should perhaps await verification of the implicit idea that the perceived intensity of contaminants, irrespective of quality, determines acceptability. Whereas this might hold true for occupancy odor and tobacco smoke odor, it may fail to hold for kitchen and bathroom odors.

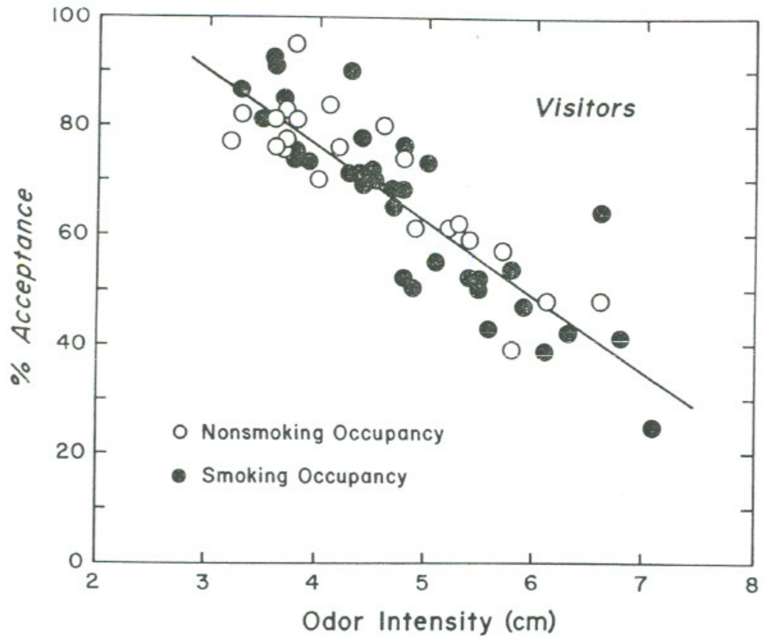


Fig. 45. Showing the correlation between percent acceptance and odor intensity (assessed by line marking) for visitors in both the occupancy odor and the tobacco smoke odor experiments. Individual values appear in Tables 1 and 2.

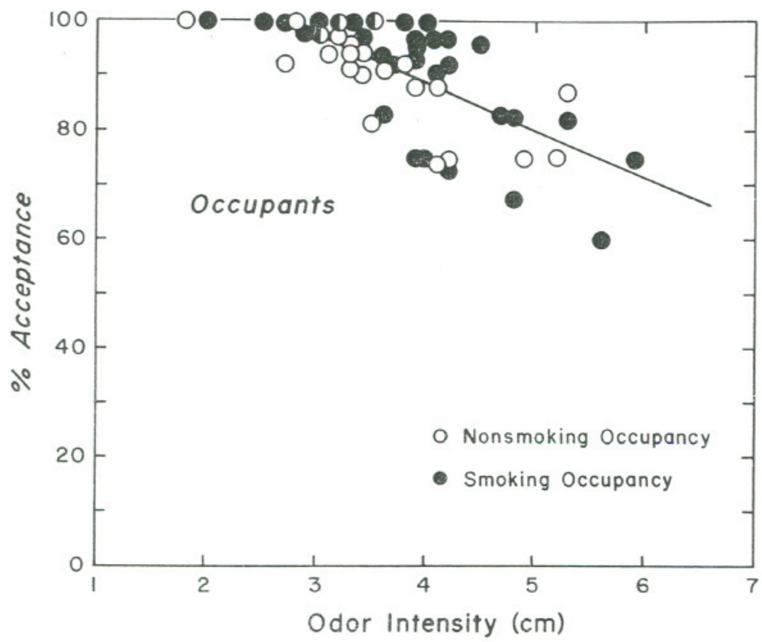


Fig. 46. Showing the correlation between percent acceptance and odor intensity (assessed by line marking) for occupants in both the occupancy odor and the tobacco smoke odor experiments.

So far, we have specified ventilation rate in terms of cfm ($L \cdot s^{-1}$) per occupant. We could also specify it in terms of fresh air changes per hour or in terms of volumetric flow per cigarette. The number of air changes per hour achieved in the investigation ranged from 2.2 in the case of 11 cfm (5.5 $L \cdot s^{-1}$) per occupant to 13.6 in the case of 68 cfm (34 $L \cdot s^{-1}$) per occupant. This roughly covers the range found in mechanically ventilated buildings. Indeed, very few buildings have a design air change rate as high as 10, yet many have rates on the order of two or three. It appears therefore that most buildings that allow smoking would fail to pass muster by the psychophysical criteria imposed in this study. We had not anticipated this finding, particularly in light of Yaglou's (21) widely known result that 40 cfm (20 $L \cdot s^{-1}$) per smoker sufficed even when smoking equalled the very high rate of 24 cigarettes per hour. That ventilation rate amounted to a little over five fresh air changes per hour in Yaglou's chamber.

Brundett (19), in a sweeping literature review of ventilation and smoking, viewed ventilation requirements in terms of volume of fresh air per cigarette. He concluded that 700 cu.ft. (20 m^3) per cigarette would suffice to maintain approximate comfort for the average person and 1400 cu.ft. (40 m^3) to maintain the comfort of virtually the entire population(including highly sensitive persons). A value of 1400 cu.ft. would translate into about 25 cfm (12.5 $L \cdot s^{-1}$) per occupant (5 air changes per hr) when occupants smoked 4 cigarettes per hour in our chamber and into about 50 cfm (25 $L \cdot s^{-1}$) per occupant (10 air changes per hr) when occupants smoked 8 cigarettes per hour. Finding little agreement from study to study in requirements based on subjective factors such as odor or irritation, Brundett apparently gave heavy consideration to concentration of particulate matter. Nevertheless, his recommendation, though generous in comparison to existing rates, would still leave the particulate concentration far above that specified by the national primary ambient air quality standard (75 $\mu g/m^3$). During smoking of 4 cigarettes per hour and a ventilation rate of 25 cfm (12.5 $L \cdot s^{-1}$) per occupant, particulate concentration in our studies averaged more than 200 $\mu g/m^3$. This exceeds the typical ambient mass concentration (particles $<$ 2.5 μm) by a factor of about seven.

In the most complete and sophisticated field survey published to date, Repace and Lowrey (30) reported that not a single one of 20 residential, commercial, and institutional spaces where smoking was permitted had particulate concentrations as low as that specified by the air quality standard for public welfare, 60 $\mu g/m^3$. With an average of about 10% of occupants smoking at any given tme, particulate levels averaged about 250 $\mu g/m^3$. A close quantitative approximation to such real world conditions occurred when our occupants smoked one cigarette every 7.5 min (8 cigarettes per hr) and the total ventilation rate equalled 272 cfm (136 $L \cdot s^{-1}$). That situation would mimic the case where 11 persons, including 3 or 4 smokers, occupied a room ventilated at the rather generous rate of 25 cfm (12.5 $L \cdot s^{-1}$) per occupant and where the smoking occupants smoked at their normal rate. Relative to that hypothetical case, our experiments merely excluded the nonsmoking occupants who act, in a sense, only as filters for respirable particulate matter. We found particulate concentrations of about 300 $\mu g/m^3$ (Fig. 38). At the statistically more common ventilation rate of 12.5 cfm (6.2 $L \cdot s^{-1}$), the concentrations equalled about 500 $\mu g/m^3$.

The ASHRAE ventilation standard specifies considerably higher ventilation in smoking than in nonsmoking areas. The modal values equal 35 cfm (17.5 $L \cdot s^{-1}$) and 7 cfm (3.5 $L \cdot s^{-1}$) per occupant, respectively. With the present recommendations, smokers would account for 87% of the demand for ventilation, even though they constitute only about 33% of the adult population. That is, the smoker makes a very heavy demand on energy for ventilation. To make matters worse, the ASHRAE recommendation for smoking occupancy seems, on the basis of our data, too low to control either odor levels or particulate concentrations. One mitigating factor is that the design ventilation rate assumes full occupancy, yet many spaces commonly have less than full occupancy. This situation in effect increases the time-averaged ventilation rate per person, though hardly by enough to meet the psychophysical and physical criteria. It would seem that Kerka and Humphreys' (22) recommendation of about 300 cfm (150 $L \cdot s^{-1}$) per cigarette, which seemed incredibly high both on absolute grounds and by comparison to other recommendations, actually has considerable merit.

There remains the question of whether data collected in an experimental chamber possess the ecological validity to lead to reasonable recommendations. How is it, for instance, that people show a willingness to occupy offices, stores, etc. where the ventilation rate falls below the values we would recommend? Part of the answer must lie in olfactory adaptation. To base ventilation criteria on the nose of the visitor carries the burden of satisfying a particularly sensitive instrument. Once in the space, however, the instrument becomes distinctly less sensitive. A high concentration of contaminant, such as a puff of cigarette smoke, can have a desensitizing influence that will make lower concentrations virtually impossible to smell for possibly many minutes. Such dynamic alterations in sensitivity have no bearing whatsoever on the particulate burden of the passive smoker. Irrespective of the psychophysical criteria for acceptability set up by our participants, the particulate concentrations measured in the chamber presumably come close to those that would be found under similar conditions of smoking and ventilation in field situations. The lack of furnishings in the chamber may retard deposition to some degree, but not enough to change the basic conclusion that current rates of ventilation can hardly control particulate concentrations adequately. Repace and Lowrey's (30) field study offers convincing support for this conclusion. Our study and a previous laboratory study by Bridge and Corn (28) also seem to offer the pessimistic conclusion that neither the current rates, nor double, nor quadruple these rates will suffice. On purely technical grounds, it would seem that only segregation of the smoker into small areas with high ventilation will suffice. Fortunately, the smoker shows considerable tolerance for the odor of cigarette smoke, even when no smoking. The smoker's personal needs for ventilation could therefore be satisfied with relatively minor difficulty in spaces set aside for smoking.

PART 3: OBSERVATIONS ON CONTAMINANT CONTROL

The experiments described so far involved hundreds of sessions and a total of more than 10,000 person-hours of data acquisition. In addition to the main experiments on ventilation, we have had the opportunity to gather smaller amounts of information on such matters as the effectiveness of granular filter media and particle filters, and on the passive decay of tobacco smoke odor. We have grouped these efforts into one chapter in order to emphasize their preliminary nature.

I. GRANULAR FILTER MEDIA

Granular filter media offer a means to reduce the concentration of organic contaminants and thereby to reduce odor (31). The most common media, activated carbon and activated alumina impregnated with potassium permanganate, see some use in ventilation systems, but principally under special conditions. For instance, one or another medium may be installed to protect sensitive electronic equipment, rare books, or persons who show hypersensitivity to various gaseous materials. At present, few systems seem to employ these media merely to reduce reliance on outdoor ventilation air. Since virtually all mechanical ventilation systems already employ partial recirculation of air for purposes of thermal control, it would seem a simple matter to install a filter in the appropriate duct and to rely more heavily on recirculation. Under such circumstances, the ventilation system would need to deliver only enough ventilation air necessary to control those notable contaminants (e.g., carbon dioxide) not captured by the filter. Although such a system may save some energy, it also presents certain problems. For instance, selection of the medium, including the appropriate mesh size, its quality, filter-bed configuration, etc., generally follows only empirical rules known by relatively few specialists, and the decision about when to replace the medium, particularly carbon, may require periodic analysis (i.e., a determination of percent saturation). Furthermore, there exists little information on the efficacy of such media in general ventilation systems. We made a few observations on how filter media would combat occupancy odor.

METHOD

Materials: Type BP 6 x 16 mesh granular activated carbon (Calgon Corp.) served as one type of filter medium. A 50/50 mixture of comparable granular activated carbon and activated alumina impregnated with $KMnO_4$, a product marketed under the name Purakol G.T. by the Purafil Corp., served as another medium. The filter bed in the duct of the chamber (see Fig. 4) accommodated 200 lb. (90 kg.) of a given medium in two trays of intermediate bed depth (1 in; 25 mm) and V configuration. Pressure drop across the filters equalled 2 mm H_2O.

Procedure: The participants and procedure were generally the same as described in the previous experiments on occupancy odor, except that after a period of occupancy the air was flowed through the filter medium for the succeeding hour. After an hour of filtration, the path of the air was switched again to by-pass the filter. Eight or 12 persons occupied the chamber and ventilation rate equalled 5 cfm (2.5 $L \cdot s^{-1}$) per occupant. Temperature equalled 23C.

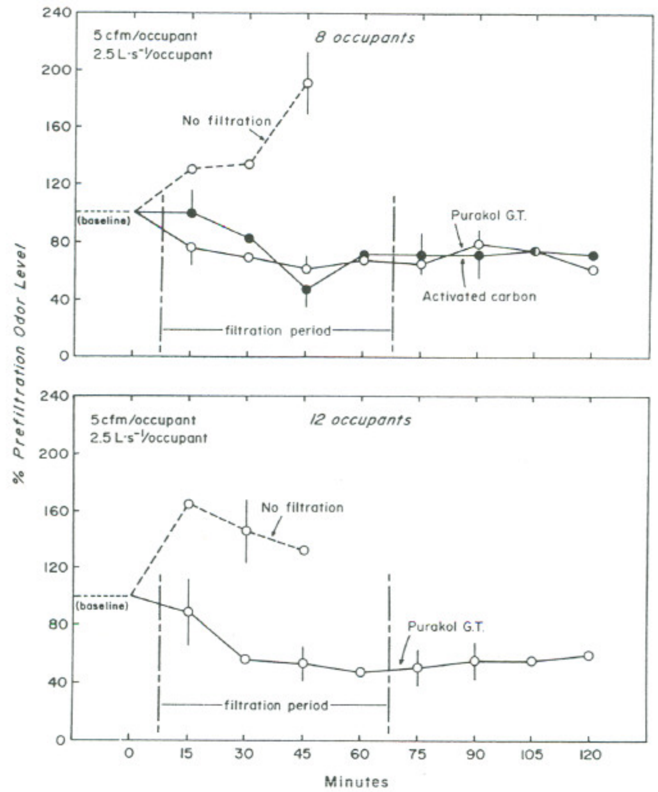


Fig. 47. Showing how Purakol G.T. and activated carbon reduced occupancy odor (butanol matching in ppm expressed as percentage of prefiltration level) in comparison to a condition of no filtration. Ventilation rate equalled 5 cfm (2.5 $L \cdot s^{-1}$) per occupant. Bars depict standard errors. Matched level in the period just before filtration, arbitrarily denoted t=0, averaged approximately 83 ppm.

RESULTS

Figure 47 displays the influence of the filter media. Both activated carbon alone and Purakol had about the same effect. Whereas odor would normally have increased over time, it decreased instead. Surprisingly, it did not rise as expected after filtration ended. This may have resulted from the intrinsic odor of carbon. Carbon filtered air has a characteristic, though relatively innocuous odor that may place an upper limit on the efficacy of the medium for control of environmental odors. Toward the end of the period of filtration, the air smelled primarily of "carbon" odor. After filtration, this odor quality faded and occupancy odor gradually reappeared. Without the apparent interference from the carbon odor, the odor level attributable to occupancy might have decreased more markedly during filtration and might have shown a more noticeable rise after filtration.

II. PARTICLE FILTERS

There exists little information regarding whether the particulate matter emitted from a burning cigarette contributes to the level of tobacco smoke odor. Yaglou and Witheridge(5) obtained evidence against a strong contribution when they charted tobacco smoke odor over time in an unventilated chamber. Two to three hours after cigarettes had been extinguished and long after visible smoke had cleared from the atmosphere, the odor level remained high. We address that same issue in the third part of this section, but first we present some observations on how particle filtration influenced the decay of odor after smoking in an unventilated chamber.

METHOD

Materials: Two particle filters were employed 1) a Honeywell electrostatic precipitator Model F50A 1009, and 2) an Airguard Type dp 4-40 fabric filter. Whereas the electrostatic precipitator eliminates respirable particles well below the size 0.1 μm, the fiber filter, when clean, loses considerable efficiency below 1.0 μm.

Procedure: The participants and procedures were generally the same as described previously, but only a 1-hr period from the end of smoking was of interest. Up until that point, four participants had smoked a total of 8 cigarettes in an hour with a ventilation rate of either 11 cfm ($5.5\ L\cdot s^{-1}$) per occupant or 20 cfm ($10\ L\cdot s^{-1}$) per occupant. At the end of smoking, the electrostatic precipitator was activated for 5 min or the fabric filter was inserted for 5 min. In a control condition, no filtration occurred.

Use of only a 5-min period of filtration arose because of detection of an ozone odor during operation of the electrostatic precipitator. After only 5 min of operation, however, the precipitator had eliminated more than 90% of the particles. Because ozone decays rather rapidly indoors, we assumed that its presence would possibly interfere with the judgment of tobacco smoke odor during only the first few minutes after deactivation of the precipitator.

RESULTS

Figure 48 displays percent reductions in TSP, CNC, and odor level (percent derived from matched ppm of butanol). Although the precipitator accelerated the decline of particles markedly, it had no reliable influence on the decline of odor level. Five min of operation of the fiber filter had comparatively little influence on decline of particles and virtually no influence on odor level. Based on the results with the precipitator in particular, it seems that particles play little role in tobacco smoke odor.

III. PASSIVE DECAY OF TOBACCO SMOKE

As noted above, Yaglou and Witheridge (5) found that tobacco smoke odor decayed very slowly in an unventilated chamber after cessation of smoking. We sought to look at this matter both psychophysically and gas chromatographically over the course of 6 hours.

METHOD

Materials: Sampling for organic constituents in the chamber employed stainless steel collecting tubes packed with approximately 90 mg of 60/80 mesh Tenax GC. The collectors (2.16 mm i.d. x 215 mm length in the packed portion) were connected to the house

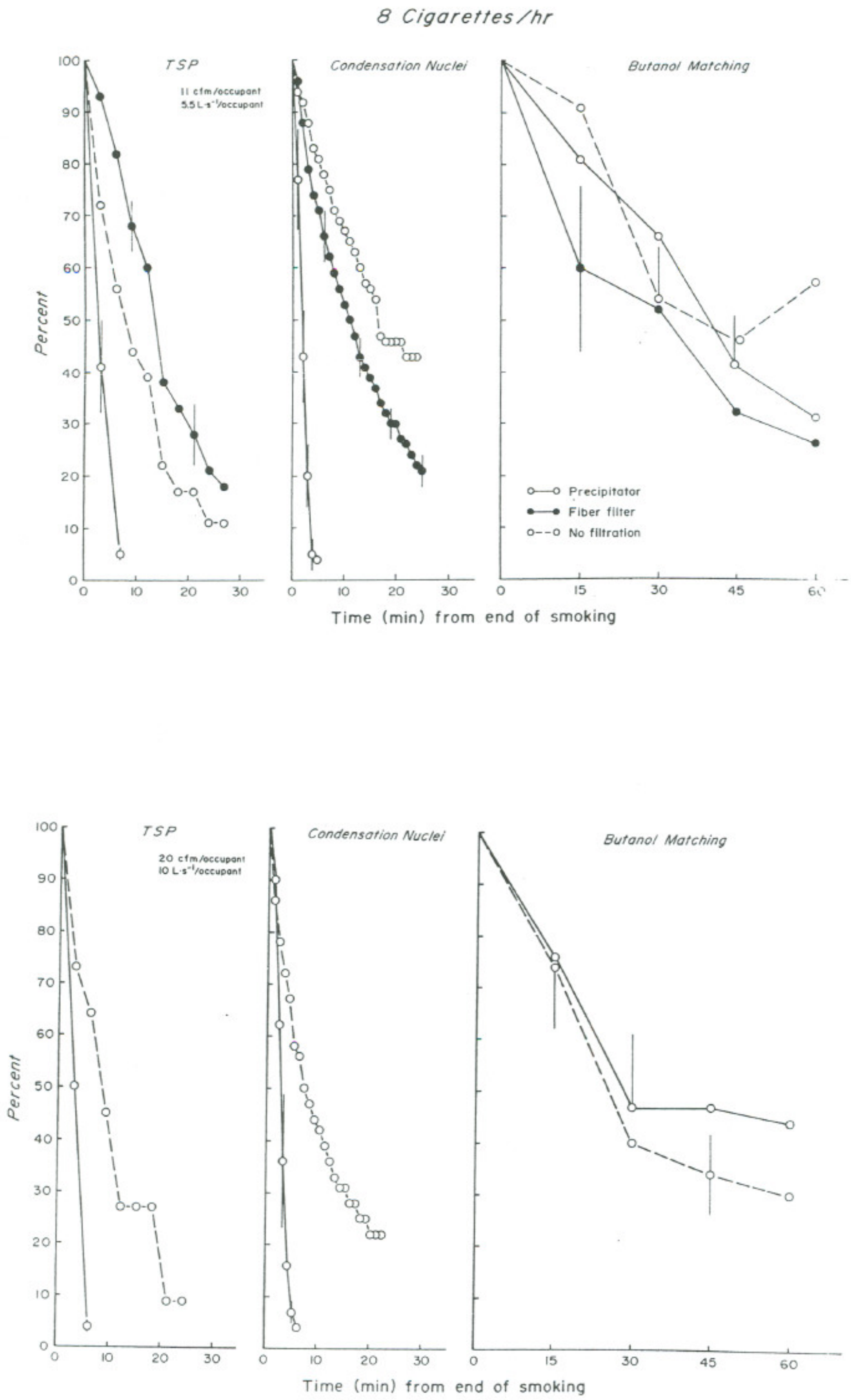


Fig. 48. Showing how percent total suspended particulate mass concentration (TSP), condensation nuclei concentration (CNC), and odor level from tobacco smoke decayed over time with and without 5 min of particle filtration in the postsmoking period. Four persons occupied the chamber and each smoked two cigarettes in the hour preceding filtration. Ventilation rate equalled 11 cfm (5.5 $L \cdot s^{-1}$) per occupant (top portion) or 20 cfm (10 $L \cdot s^{-1}$) per occupant (bottom portion). In the cases where the number of observations or runs permitted, standard errors were calculated and are shown by bars. Matched level of butanol at t=0 averaged approximately 230 ppm.

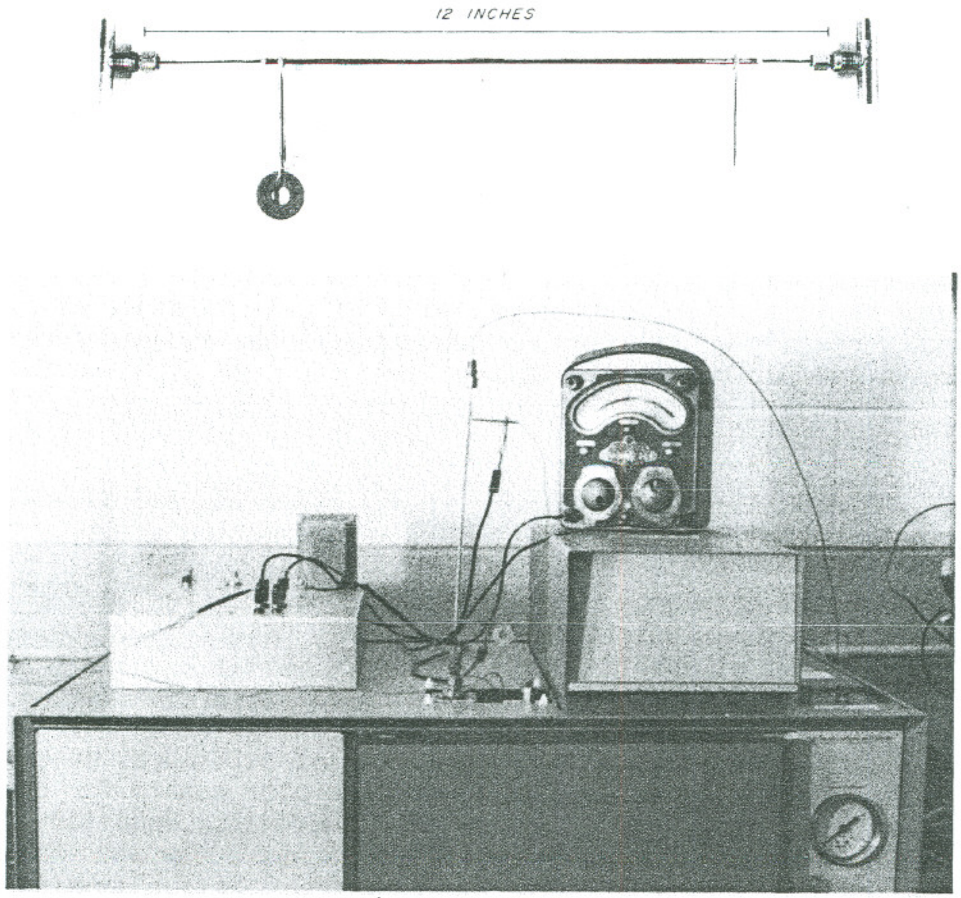


Fig. 49. Upper part shows the Tenax-filled collector developed at IITRI, Chicago, Ill. The fittings placed on the ends serve to prevent loss of material. Lower part shows the set-up for thermal desorption of the contents trapped in the collector. One end of the collector is fitted into injection port of the gas chromatograph. A stream of nitrogen flowing through the collector during resistance heating of the side arms (power supply and VOM shown)transports the contents into the chromatograph.

vacuum line which drew a 2-L sample of air through any given collector over the course of an hour. Material adsorbed onto the Tenax could be retained in the collector for days through the use of Conax compression fittings placed over the ends of stainless steel extensions (0.76 mm i.d.) brazed onto the main part of the collector (see Fig. 49).

Thermal desorption, accomplished by means of resistance heating of the collector to 280 C during flushing with nitrogen, provided the means to pass the collected material into a gas chromatograph. For further details regarding collection and desorption see Jarke, Gordon, and Dravnieks (32).

A Hewlett-Packard gas chromatograph Model 5840A equipped with a flame ionization detector and capillary injection system was modified at the injection port to accept the extensions of the collector. The chromatograph was operated with a split ratio of 60 to 1 and separation of constituents was achieved with a 25 m x .25 mm o.d. fused silica open tubular column coated with methyl silicone SP-2100. Figure 50 shows the thermal conditions of operation.

Liquid injection of a series of normal alkanes provided a retention index scale and allowed estimation of the hydrocarbon number for the materials captured by the Tenax collectors. The injected alkanes also permitted a quantitative estimate of the levels of contaminants present in the air samples.

Procedure: The participants and procedures were generally the same as described previously. Four occupants smoked a total of 10 cigarettes during a 1.5-hr period with the ventilation rate at 11 cfm (5.5 $L \cdot s^{-1}$) per occupant. Temperature equalled 23C. Shortly after smoking ceased, ventilation was turned off, the occupants vacated the chamber, and ashtrays and butts were removed.

RESULTS

As Fig. 51 shows, odor decayed relatively slowly after the end of ventilation. Throughout that 4.5-hr period, the odor never fell to presmoking values.

Prior to the period of occupancy, the Tenax collectors picked up small quantities of only relatively low molecular weight compounds. When occupants entered, the number of substances present at quantities above approximately 0.1 ppm tripled. In Fig. 52, a retention time printed above a peak indicates the presence of a substance at or above 0.1 ppm and the integrated area under such peaks formed our index of total hydrocarbons. During active smoking, the number of substances present above 0.1 ppm tripled again, as did the total number of integrator counts for those substances. Whereas the total number of counts prior to occupancy equalled 700 or about 0.7 ppm, the number during occupancy equalled 2300 or about 2 ppm and the number during smoking equalled 7200 or about 7 ppm (see Fig. 53). Active smoking caused a particular increase in higher molecular weight compounds. The compounds detected at 0.1 ppm during occupancy fell generally between C_5 and C_8, whereas those added or amplified during smoking fell commonly between C_8 and C_{14}.

In the first two hours after smoking, some peaks disappeared and some appeared for the first time, but the total number of integrator counts equalled 7000-8000. Thereafter, the number first fell (third hour post-smoking) and then rose again (fourth hour). This decay and subsequent rise appears in the psychophysical data too. Although there exists no certainty that all of the Tenax filled tubes collected with equal efficiency, the chromatographic records depict a pattern of reasonable but hardly perfect qualitative stability.

IV. DISCUSSION

The results in this section reinforce the previous conclusions that occupancy odor and tobacco smoke odor differ considerably in their tractability. The second experiment (particle filtration) and third experiment (passive decay) proffer little hope that tobacco smoke odor will lend itself to ready control. The odor during active smoking seems to arise almost exclusively from gas phase products and hardly at all from organic materials condensed on particles. Yet the particles complicate the

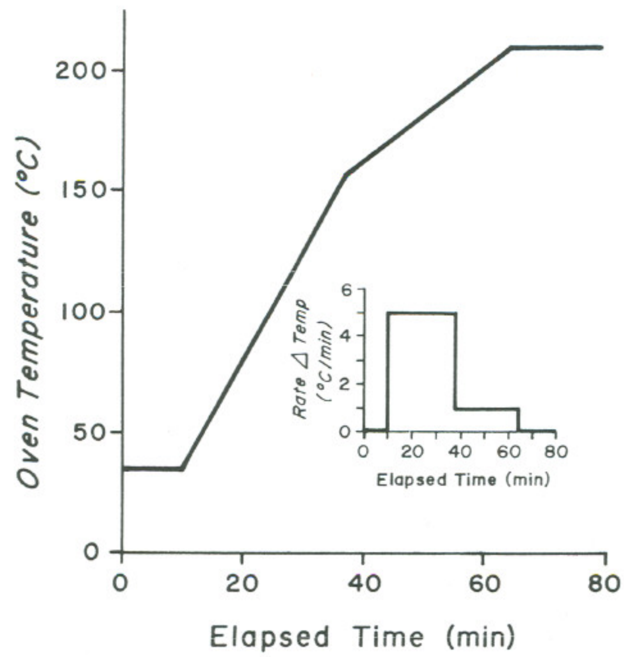


Fig. 50. Temperature program for the oven of the gas chromatograph. Temperature at the injection port equalled 300C.

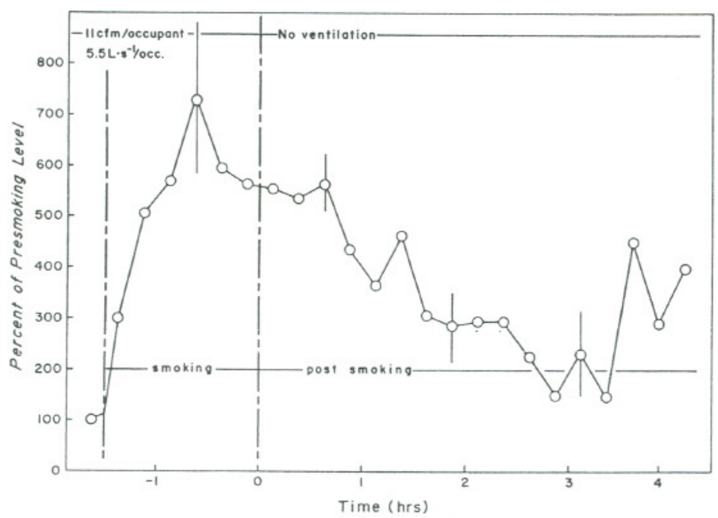


Fig. 51. Showing how odor level (percentage of presmoking level) varied before, during, and after smoking. Before and during smoking, ventilation rate equalled 11 cfm (5.5 $L \cdot s^{-1}$) per occupant for 4 occupants who smoked 3 cigarettes each during the 1.5-hr period of smoking. Ventilation ended at point labeled zero (0), when participants stopped smoking and vacated the chamber, taking ashtrays and butts with them. A fan operating inside the chamber and a blower that moved air through the sniff box maintained a well stirred environment.

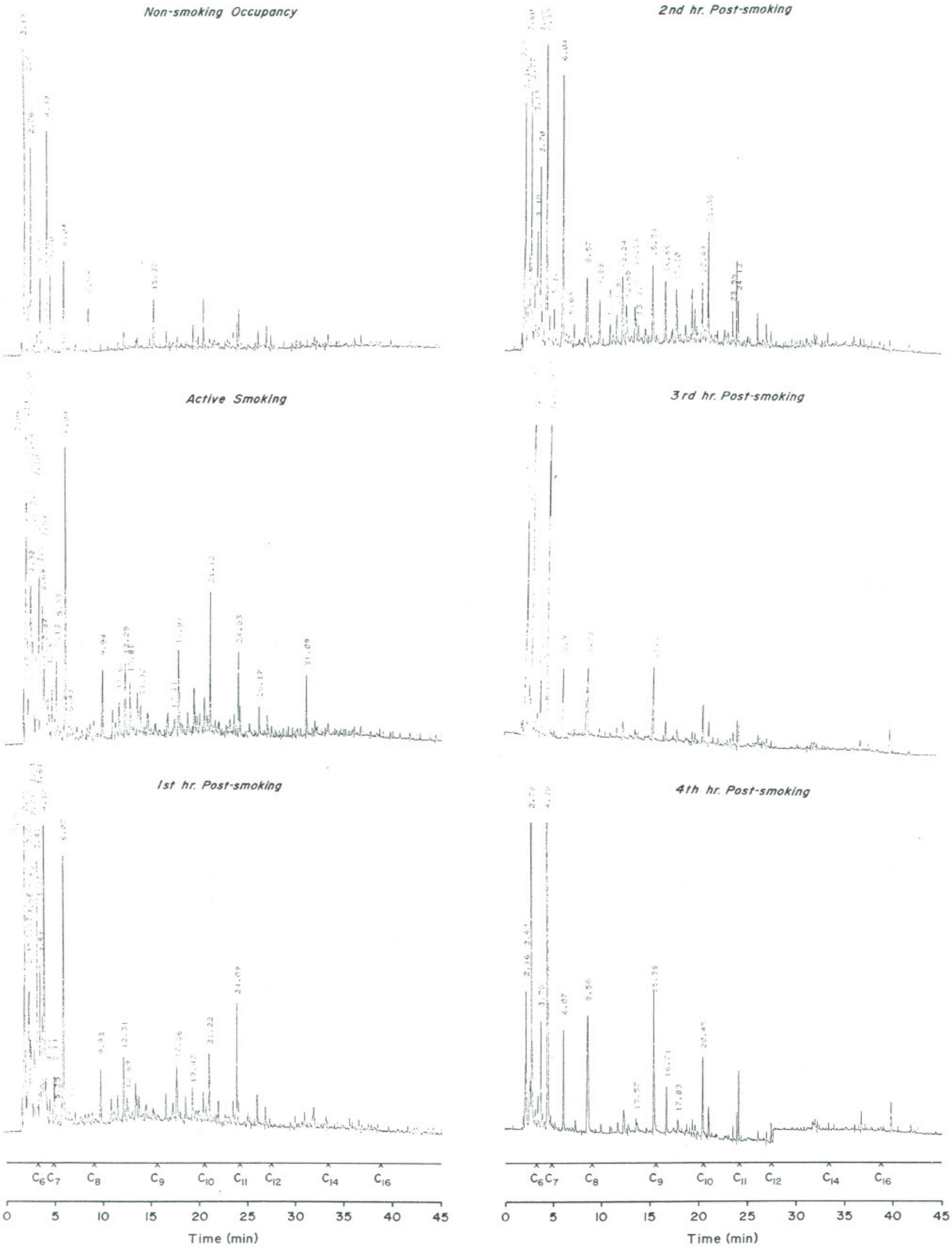


Fig. 52. Gas chromatograms for successive 1-hr samples from the period of nonsmoking occupancy (4 occupants), active smoking (12 cigarettes in 1.5-hr), and four subsequent hours. Peaks annotated with retention times represent concentrations of 0.1 ppm (v/v in air) or above. The cumulative area under the annotated peaks provided a rough indication of total hydrocarbons (see Fig. 53). The scale at the bottom indicates, for reference, retention times of various normal alkanes.

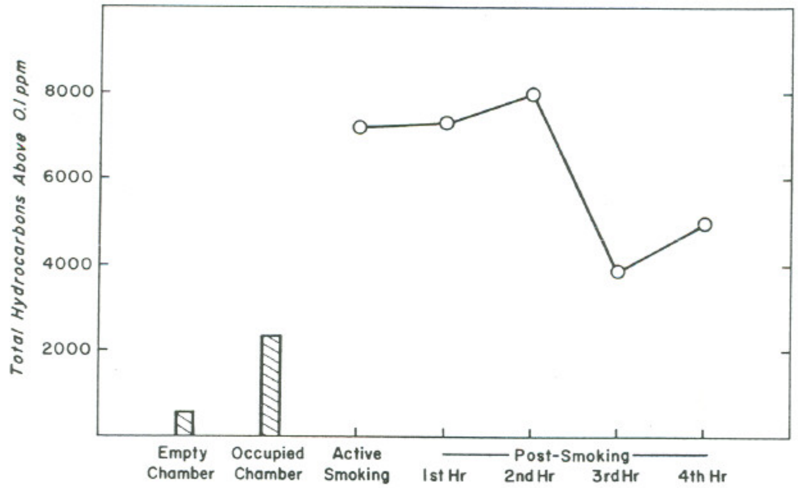


Fig. 53. Total integrator counts ("total hydrocarbons") for substances present above 0.1 ppm in the ventilated chamber prior to occupancy, during occupancy, and during and after smoking.

problem of cleaning the air. Furthermore, even after they diffuse to surfaces, the particles may eventually release gases in such a way as to prolong the objectionability of the odor. In spite of this possibility, we found that the odor quality perceived after smoking remained about the same as during smoking. In this instance, the quality did not turn stale and sour as it generally does, when ashtrays and butts remain in the room.

The chromatographic records hardly allow us to point with any certainty toward particular odor-relevant constituents in the air of the chamber. The many small peaks below the sensitivity of our integrator may conceivably carry much more odor-relevant information than the large peaks. Hence, the large peaks are more or less symbolic of the chemical complexity and diversity that may exist below our analytical threshold. The persistence of tobacco smoke constituents tends to argue against the use of intermittent or variable volume ventilation based merely on occupancy in any spaces where smoking occurs.

GENERAL SUMMARY AND CONCLUSIONS

The report has dealt with two extremes on the continuum of common indoor odor nuisances: occupancy odor and tobacco smoke odor. Occupancy odor offers relatively little challenge to ventilation systems. Our experiments imply that a modest amount of ventilation, 5 to 10 cfm (2.5 to 5 $L \cdot s^{-1}$) per occupant, will suffice to control the odor to a degree that more than three-quarters of visitors will find acceptable. The rule holds for the temperature range encountered most frequently indoors, 20 to 25.5C, under conditions of moderate humidity. The rule also seems approximately independent of the number of persons inthe space. In this respect, it differs considerably from Yaglou's rule that the amount of ventilation per person must increase as the air space per person decreases.

Three types of odor intensity judgments (butanol matching, magnitude estimation, and line marking) tended to reinforce one another, i.e., to lead to approximately the same conclusions. Butanol matching and magnitude estimation were used here to describe how odor varied over time, whereas line marking yielded only a single number of odor intensity under approximately steady-state conditions. Nevertheless, line marking proved rather successful as a simple indicator of a visitor's view of acceptability. Like the other judgments, line marking implied that a combination of high temperature (25.5C) and high humidity ($>$ 70% RH) creates odor problems that may require more than twice as much ventilation as moderate humidity.

Occupants, as opposed to visitors, showed little concern about the degree of occupancy odor, presumably because persons in a space for even a few minutes exhibit olfactory adaptation. Ventilation rates as low as 5 cfm (2.5 $L \cdot s^{-1}$) per occupant met virtually complete acceptance from occupants as long as humidity remained in the moderate range. High temperature and humidity met noticeably less acceptance on various grounds: apparent humidity, stuffiness, warmth, and, somewhat surprisingly, odor.

The generalities uncovered in the study of occupancy odor have obvious limitations insofar as they arise from 1) the use of an unfurnished chamber that offers less than the customary opportunity for airborne materials to adsorb onto or to be absorbed by furnishings, 2) structured judgmental conditions somewhat remote from real world situations, 3) conditions of sedentary occupancy, and 4) the use of a ventilating system that assures rapid and rather homogeneous dilution of contaminants with ventilation air. The absence of furnishings and the structured judgmental conditions which required visitors to focus on the odor would seem likely to cause the research to overestimate the nuisance of occupancy odor relative to real world settings. The restriction to sedentary occupancy, on the other hand, would seem likely to lead to lower generation of contaminants and hence to an underestimation of the nuisance relative to real world conditions. Nonsedentary occupancy probably deserves special attention in future studies.

The use of an approximately ideal ventilating system presumably eliminates some of the variability that could arise from poor mixing. A poor system can lead, for example, to poor clearance in one part of a room yet good clearance in another part. The well known study of Yaglou, Riley, and Coggins (3) may have been influenced in a systematic way by poor mixing at relatively high ventilation rates. Except for a disparity that may have arisen from that limitation, the present results agree reasonably well with those of Yaglou and colleagues. In terms of the relation between odor intensity and acceptability, the results also agree in general with the field study of Duffee and colleagues (13).

The outcome of the study of tobacco smoke odor probably has fewer limitations than that of the study of occupancy odor. As a contaminant, tobacco smoke tends to dominate others wherever it occurs. Hence, such matters as sedentary vs non-sedentary occupancy and the presence or absence of furnishings probably have little relevance to the level of annoyance caused by tobacco smoke during active smoking. Furthermore, at present many persons do focus on it and judge it rather deliberately in real world situations. The attention it receives derives in part from its immediate sensory impact as an odorant and irritant and in part from its possible health impact. Standards for ventilation of this contaminant should consider both aspects.

As soon as a person lights a single cigarette in a normally ventilated room of small to moderate size, both odor magnitude and concentration of particulate matter climb to unacceptable levels. Successive cigarettes will drive the levels up farther and only an hour or more of continued ventilation after heavy smoking may suffice to bring the levels down to an acceptable point. Wherever smoking occurs regularly, the air in that space will commonly violate the primary national ambient air quality standard for total suspended particulate mass concentration, though generally not the standard for carbon monoxide.

Although the odor levels attained during smoking far exceed those attained during mere occupancy, visitors seem to set about the same criterion of acceptable intensity for both contaminants. It turns out, however, that the nonsmokers in the sample of visitors set a far more stringent criterion for tobacco smoke than do smokers. In fact, nonsmokers set a criterion apparently unachievable with mere ventilation.

During sessions devoted to smoking, only smokers occupied the chamber. As expected, these persons showed good tolerance for odor. Nevertheless, they showed somewhat less tolerance than expected for high humidity, temperature, and stuffiness. Perhaps one low level source of discomfort, in this case the smoke from their own cigarettes, causes an amplification of the discomfort that persons feel from other sources.

Of the various previous suggestions regarding ventilation requirements for places with cigarette smoking, Kerka and Humphrey's (22) suggestion of 300 cfm (150 $L \cdot s^{-1}$) per cigarette comes closest to the value we might recommend. Although that value may have seemed too high when first proposed in 1956, it actually seems too low now. To illustrate, when occupants in our chamber smoked a total of four cigarettes per hour and the total ventilation rate equalled 272 cfm (136 $L \cdot s^{-1}$), both odor intensity and particulate mass concentration reached unacceptable levels during the first cigarette and continued to do so even in the intervals between cigarettes. Although a particle filter, such as an electrostatic precipitator, could rapidly reduce the particle concentration to an acceptable level, it will apparently leave the odor level approximately the same. An adsorbent filter, such as activated carbon, put in series with a particle filter might possibly reduce gaseous contaminants to an acceptable odor level, but such filters pose their own difficulties (maintenance, life span, eventual breakthough of contaminants).

Occupancy odor and tobacco smoke odor represent extremes of the continuum of indoor air contaminant problems in more than one way. One is innocuous, the other harmful. One is easy to filter, the other relatively complicated. One seems easy to ventilate for, the other difficult and perhaps impossible. One seems possible to control with somewhat less energy than is used presently, the other only with considerably more energy.

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