LBL-9578 c.2
EEB-Vent 79-19
UC-41

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT DIVISION

VENTILATION AND ODOR CONTROL: PROSPECTS FOR ENERGY EFFICIENCY

Final Report of Phase I

William S. Cain, Larry G. Berglund,
Richard A. Duffee and Amos Turk

RECEIVED
LAWRENCE
BERKELEY LABORATORY

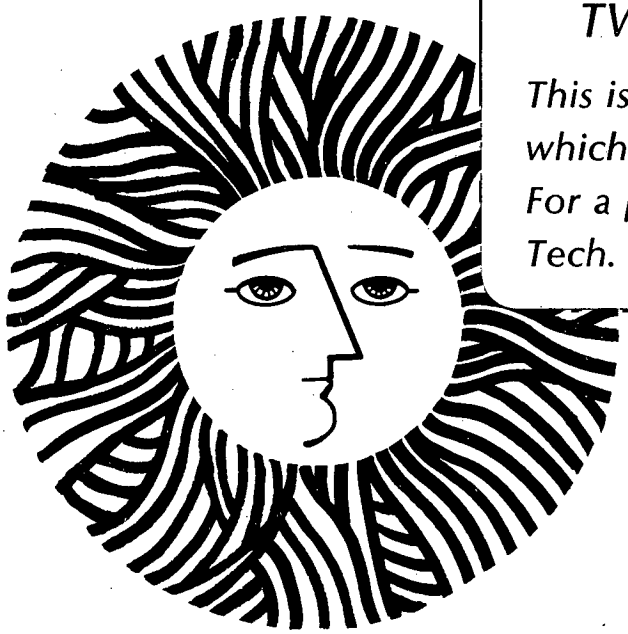
MAR 14 1980

LIBRARY AND
DOCUMENTS SECTION

November 1979

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 6782.



LBL 9578 c.2

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-9578
EEB-Vent 79-19

VENTILATION AND ODOR CONTROL: PROSPECTS FOR ENERGY EFFICIENCY

A Review of the Literature, with Recommendations for Research

Final Report of Phase I

William S. Cain and Larry G. Berglund
John B. Pierce Foundation Laboratory
New Haven, Connecticut

Richard A. Duffee
TRC Environmental Consultants
Weathersfield, Connecticut

Amos Turk
City University
New York City, New York

November 1979

Prepared under UCLBL P.O. No. 4622602 for the Energy Efficient Buildings Program, Energy and Environment Division, Lawrence Berkeley Laboratory. Principal Investigators: Craig Hollowell and Arthur Rosenfeld.

The work described in this report was funded by the Office of Buildings and Community Systems, Assistant Secretary for Conservation and Solar Applications of the U.S. Department of Energy under contract No. W-7405-ENG-48.

VENTILATION AND ODOR CONTROL: PROSPECTS FOR ENERGY EFFICIENCY

A review of the literature, with recommendations for research

William S. Cain, Principal Investigator

Larry G. Berglund

Richard A. Duffee

Amos Turk

Submitted by:

John B. Pierce Foundation Laboratory
290 Congress Avenue
New Haven, CT 06519

Date: November 1979

Prepared for:

Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

CONTENTS

EXECUTIVE SUMMARY i

INTRODUCTION 1

Odors 1
Odor Sources and Energy Efficiency 2
Energy Conservation and Ventilation Codes 4
Plan of the Report 5

INVESTIGATIONS OF VENTILATION REQUIREMENTS 7

New York State Commission on Ventilation 7
Derivation of Functional Relations 12

ODOR CONTROL 24

Deodorization of Recirculated Air by Granular Media 24
Activated Carbon 25
Other Granular Media 28
Alternatives to Granular Media 30

ODOR PERCEPTION 32

Nonuniformity 32
Nonlinearity 34
Interactive Phenomena 36
Lability 38
Common Chemical Sense 40
Physical Factors in Odor Perception and Ventilation 41
Odor Perception and Health: Some considerations 46

ANALYTICAL AND PSYCHOPHYSICAL MEASUREMENT 48

SUMMARY AND PROSPECTS 53

REFERENCES 56

EXECUTIVE SUMMARY

Ventilation serves to dilute contaminants that arise in occupied spaces. Generally, the most bothersome contaminants comprise organic chemical substances present only in relatively small amounts. Even in small amounts, these may impart a definite odor to a space. Accordingly, quantitative requirements for ventilation comprise, in effect, requirements for odor control. Because the odors of human bodies, tobacco, smoke, cooking, and waste defy simple analysis by instrumental means, the most direct way to decide ventilation requirements is to perform psychophysical experiments. These can connect the magnitude and objectionability of odor to such variables as source and magnitude of contaminants (e.g., number of occupants, number of cigarettes smoked per hour), rate of ventilation, temperature, humidity, duration of occupancy, use of filter media, and various secondary variables.

The realization that requirements for mechanical ventilation rest rather directly on the need to control odors came about only gradually. Before the 1920s, mechanical ventilation requirements were generally seen to arise from the need to control uncharacterized, but putatively toxic gases generated during occupancy. Thereafter, particularly during the 1930s, the basis for ventilation shifted from health effects to welfare effects. It then became clear that ventilation rates necessary to protect welfare (to eliminate annoyance, discomfort) offered more than enough air to protect health. Psychophysical experiments on occupancy odor, performed in that era, provided the underpinnings for modern ventilation standards. Those experiments, primarily the conception of C. P. Yaglou and associates, have exerted more leverage than ever intended. Admittedly incomplete in their time, the experiments on ventilation requirements deserve reinspection and extension with modern facilities and modern methods of analytical chemistry, particulate monitoring, and psychophysical evaluation. Five broad issues of particular importance include 1) the reported need for vastly higher ventilation rates per person under crowded than under uncrowded conditions, 2) the stability of various odorous contaminants (e.g., tobacco smoke odor) after removal of the source, 3) the role of temperature and humidity in the generation and perception of odorous contaminants, 4) the possibility that indoor air cleaning via filtration can eliminate the need for high quantities of ventilation air and can thereby save energy, and 5) whether results obtained in an "ideal" ventilation system (i.e., an aluminum lined room with precise control of environmental variables and air delivery) will generalize to field situations. These, and various associated issues (e.g., the contribution of particulate matter to tobacco smoke odor, the difference in odor tolerance between an occupant in a room and a visitor to a room), form the basis for newly begun laboratory and field experiments on ventilation and odor control, with particular emphasis on the quest for energy efficiency in ventilation.

INTRODUCTION

The indoor air generally contains a great variety of substances, organic and inorganic, present only in low concentrations. In a well-designed and well-tended building, these substances often exist at levels low enough to lack discernible impact on occupants. At levels high enough to have adverse impact, the substances are viewed as contaminants.

A contaminant may act upon such biological targets as the airways, the liver, the central nervous system, and so on. Some contaminants may cause an immediate reaction, others a much delayed or a cumulative reaction. Some may pose little hazard when inhaled alone, but an amplified hazard when inhaled along with other contaminants. Some may have little impact on the majority of persons but a large impact on a sensitive minority.

Generous ventilation has provided the traditional means to combat accumulation of indoor contaminants. Nevertheless, the cost of ventilation, on the average more than one-quarter of the operating cost of a building, increases proportionally with the cost of energy and therefore provides considerable incentive to search for energy efficiency. The present report will deal primarily with technical features of ventilation and the control of odorous contaminants. It will pursue a dual goal: to maintain acceptable air quality indoors and to achieve energy efficiency in the maintenance of air quality.

Odors

In addition to any ability to cause adverse impact, most airborne organic substances possess the common ability to excite olfaction (1). Many become detectable by smell at concentrations well below one part-per-million (ppm). Indeed, some evoke strong, even overpowering odors at concentrations in the ppm range.

Like other sense modalities the sense of smell behaves as an adaptive channel of information. For instance, olfaction manages to block the ingestion of various unhealthful substances (e.g., spoiled meat) that might be deemed acceptable by taste. When used to evaluate the properties of substances taken into the mouth, olfaction serves as a "contact" sense in a manner similar to taste. Olfaction also serves as a "distance" sense, a channel for information about objects outside the body. When using the modality in this way, a person can readily succumb to the temptation to ascribe to the odorous air characteristics more properly attributed to the source of odorant. Hence, foul smelling air can seem dangerous in itself rather than merely a signal of the presence of unsanitary conditions. A passage regarding the views of the eminent public health physician Charles V. Chapin illustrates a common confusion (2):

> Probably the most conspicuous aspect of the sanitary environment of Providence (as of other cities) in 1884 was the stench. It had odors from its hundreds of stables, its polluted streams, its dead dogs or horses, and its thousands of foul privy vaults and cesspools. When the odors became so intense that even the people who lived among them were nauseated, it is no wonder that many persons associated diseases with bad smells. And when disease did come out of certain kinds of foul smelling dirt, it was only logical for people to fear and wish to eliminate filth ... Chapin did not fear odors as such. He was one of a few in America before 1885 who followed the English sanitarian John Simon in pointing out that the danger from filth was not in the stench but in specific disease germs. [p. 45]

In the late 19th century when physiologists began to experiment in earnest on the biological basis for ventilation, the question of acceptable odor levels indoors also attained prominence. Various scientists of the time considered the organic substances given off by human bodies as particularly harmful, even lethal (3):

> Organic matter is given off from the lungs and skin, of which neither the exact amount nor the composition has been hitherto ascertained. The quantity is very small, but of its importance there can be no doubt ... Since this organic matter has been proved to be highly poisonous, even apart from carbon dioxide and vapor, we may safely infer that much of the mischief resulting from the inspiration of rebreathed air is due to the special poisons exhaled by the body.

Absence of techniques to detect small amounts of organic vapors meant reliance on the nose as an indicator of safety. Since that era, it has become clear that body odor in particular carries little hazard. Nevertheless, throughout this time odors have never ceased to play a strong role in the determination of ventilation requirements. Whether for reasons of health or esthetics, odors will continue to figure in ventilation practice. Therefore, any effort to discover ways to conserve energy in ventilation must confront the issue of how odors arise, how they are perceived, and how to control them.

Odor Sources and Energy Efficiency

Odors may arise from almost any indoor activity. Tobacco smoke forms a particularly notorious odor nuisance. Its persistence and its change in character over time (i.e., from fresh, but irritating, to stale and sour) account for much of its notoriety. Places of habitual smoking may never lose their odor even when ventilated continuously at very high levels. The cost of such high rates of ventilation gives incentive to displace or eliminate the source. Where possible, elimination of a source of odor provides the most economical and energy efficient means of control. Odor problems in the workplace, for instance, often arise from poor "housekeeping." The same can hold true in residences and in commercial and institutional buildings. Such housekeeping chores may include, among other things, cleaning of ducts and cooling coils and removal of filters in a ventilation system. This kind of housekeeping acknowledges that the system may become a secondary source of odor from dust, bacteria, mold, spores, and adsorbed organic materials.

In many instances, odors arise from sources (e.g., kitchen stoves, toilets) that allow some control of the source, but not complete removal. The most energy efficient means to cope with such high intensity sources may include local exhaust with perhaps some recirculation of the exhaust air. In general, however, odor control will derive from the need to cope with such things as effluvia from bodies, emanations from building materials, and ongoing activities of occupants (e.g., eating, drinking). These matters require general ventilation and pose the energy relevant issue of whether a space should continuously receive the amount of ventilation air dictated by the so-called design occupancy. Many spaces are commonly occupied at much lower levels. The matter of ventilation on demand, achievable through monitoring and control of concentrations of carbon dioxide, oxygen, carbon monoxide, or other, as yet, unspecified contaminants,will receive little direct attention here. Nevertheless, this manner of gaining control over the atmospheric environment in a building is potentially compatible with both high indoor air quality and low expenditure of energy.

Energy Conservation and Ventilation Codes

The present report will give primary consideration to odors, but will necessarily pay some attention to the thermal attribute of the indoor environment. These factors play companion roles. Ventilation can serve simultaneously to bring the indoor environment under thermal control, e.g., using outdoor air to cool a warm space, as well as to dilute chemical contaminants. Furthermore, occupants may confuse thermal and chemical attributes perceptually, viz., may decide that stuffiness arises from poor air quality as opposed to overly warm air. The intimate relationship between these factors takes on particular importance in efforts to conserve energy. Any reduction in the amount of ventilation air normally necessary to control odors will reduce the energy consumed to heat, cool, humidify, or dehumidify that air. Such savings can add to those achieved through lowering the settings of thermostats in winter and raising the settings in summer.

Within the last few years it has become common for jurisdictions to adopt model building codes. The codes include those of 1) the Building Officials and Codes Administrators International (BOCA), used mainly in the midwest and northeast, 2) the International Conference of Building Officials (ICBO), used mainly in the west, and 3) the Southern Building Code Congress International (SBCCI) used mainly in the south and southeast. In some instances, a particular model code governs building practices in all local jurisdictions within a state. In other instances, local officials will have the opportunity to choose between the state code or a specified model code. In some states (e.g., Texas), one model code will prevail in one area and another model code in another area. Irrespective of such seeming complications, the country has in fact begun to converge upon uniformity in building codes and accordingly in ventilation codes.

In a particularly strong gesture toward uniformity, the three model code groups (BOCA, ICBO, SBCCI) worked together with the National Conference of States on Building Codes and Standards (NCSBCS) to draw up an energy conservation code (The Code for Energy Conservation in New Building Construction). This code, in actuality a section of a total code, has already become or will become part of the BOCA, ICBO, and SBCCI model codes. The code for energy conservation finds its parentage in Standard 90-75 (Energy Conservation in New Building Design) of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

Table 1 shows that virtually all large jurisdictions have already or will soon conform to energy conservation standards through adherence to one or another model code or through the adoption of a separate state code rooted in a model code or ASHRAE Standard 90-75. Indeed, only five jurisdictions fail at present to show overt action toward the adoption of an energy-efficient code. The information in Table 1 was gathered by NCSBCS and disseminated on May 25, 1979.

The ventilation component of the energy conservation model code derives from ASHRAE Standard 62-73, Standards for Natural and Mechanical Ventilation.* That standard lists ventilation requirements per occupant for a great variety of residential, commercial, industrial, agricultural, and institutional spaces. The standard specifies, space by space, two requirements: minimum and recommended. The recommended requirements actually form an interval, e.g., 15-20 cfm (7.5 - 10 L/s) per occupant. Minimum requirements fall on the average 30% below the midpoint of the recommended range. Table 2 gives examples for a few spaces.

*Standard 62-73 is currently under revision. A revised standard will probably appear in 1980.

Table 1

NCSBCS Survey of Energy Conservation Codes

Jurisdiction	Energy Conservation Code	Jurisdiction	Energy Conservation Code
Alabama	SBCCI	Nebraska	(ICBO)
Alaska	(ASHRAE 90-75)	Nevada	MCEC
Arizona	(State Code)*	New Hampshire	MCEC
Arkansas	(State Code)*	New Jersey	BOCA
California	State Code	New Mexico	ICBO
Colorado	MCEC	New York	State Code*
Connecticut	State Code*	North Carolina	State Code
Delaware	(MCEC)	North Dakota	ICBO
District of Columbia	(City Code)	Ohio	MCEC
Florida	State Code*	Oklahoma	None
Georgia	MCEC	Oregon	ICBO
Hawaii	ICBO	Pennsylvania	(ASHRAE 90-75)
Idaho	ICBO	Rhode Island	ASHRAE 90-75
Illinois	(State Code)*	South Carolina	SBCCI
Indiana	MCEC	South Dakota	(MCEC)
Iowa	MCEC	Tennessee	MCEC
Kansas	State Code	Texas	(MCEC)
Kentucky	MCEC	Utah	MCEC
Louisiana	(MCEC)	Vermont	(ASHRAE 90-75)
Maryland	(ASHRAE 90-75)	Virginia	BOCA ASHRAE 90-75
Massachusetts	MCEC	Washington	State Code
Maine	(State Code)	West Virginia	None
Michigan	ASHRAE 90-75	Wisconsin	State Code*
Minnesota	ASHRAE 90-75	Wyoming	ICBO
Mississippi	(MCEC)	American Samoa	MCEC
Missouri	(MCEC)	Guam	ICBO
Montana	MCEC	Puerto Rico	MCEC

Key: ( ) Denotes Legislation Pending
ASHRAE 90-75 ASHRAE STANDARD 90-75
BOCA Model Code, Building Officials & Code Administrators International, Inc.
ICBO Model Code, International Conference of Building Officials
MCEC Model Code for Energy Conservation in New Building Construction
SBCCI Model Code, Southern Building Code Congress International,Inc.
Asterisk(*) denotes obvious incorporation of energy conserving aspects of a model code or ASHRAE 90-75. Codes or pending codes for California, Maine, and North Carolina also include some such aspects.

Table 2

Examples of Ventilation Requirements Per Occupant
Recommended in ASHRAE Standard 62-73.

	Minimum		Recommended	
Residential bedrooms	5 cfm	(2.5 L/s)	7-10 cfm	(3.5-5 L/s)
Conference rooms (small)	20	(10)	25-30	(12.5-15)
Public rest rooms	15	(7.5)	20-25	(10-12.5)
Classrooms	10	(5)	10-15	(5-7.5)
School libraries	7	(3.5)	10-12	(5-6)

ASHRAE Standard 90-75 on energy conservation specifies use of the minimum values from Standard 62-73. This means that new buildings should now deliver approximately 70% of the outdoor air delivered prior to the energy conservation standard. These new recommendations have considerable impact because they form the ventilation recommendations of the Code for Energy Conservation in New Building Construction jointly prepared by BOCA, ICBO, NCSBCS, and SBCCI. In essence, then, the various code-bodies of the United States have shown a strong desire to achieve both uniformity and energy efficiency in ventilation.

ASHRAE's assessment of ventilation requirements arises mainly from consensus regarding the outdoor air necessary to maintain indoor comfort. As will become evident below, the minimum requirements bear similarity to the outcome of laboratory research on the acceptability of odors generated during occupancy.

Plan of the Report

The remainder of this report will highlight the various factors that play a role in the determination of ventilation requirements for odor control. First, the report will review studies that uncovered and quantified the connection between odors and ventilation requirements. Although motivated by an interest in public health and hygiene, such studies were generally reported in the engineering literature. Not surprisingly, therefore, most hygienists and public health specialists have traditionally paid little attention to chemical contaminants in the residential, commercial, and institutional environments. The presumed adequacy of ventilation has allowed such professionals to focus on chemical contaminants in the workplace and in the ambient air. Recent discoveries regarding excessive levels of formaldehyde in buildings lined with chipboard (4), excessive levels of particulate matter in the vicinity of smokers (5), and excessive levels of oxides of nitrogen in homes with gas stoves (6), have, in conjunction with the need for energy efficiency, refocused attention on the origin and adequacy of nonindustrial ventilation rates.

Subsequent to a review of the research basis for modern ventilation rates, the varieties of odor control applicable indoors will receive attention. The section on control will deal at length with chemical and engineering considerations in the use of granular filter media, the most practical means of indoor odor control. In the present context, the term odor control refers to the elimination of small amounts of gaseous materials. Some such materials happen to evoke odor and provide no other incentive for control. Nevertheless, the control procedures will eliminate many

inodorous as well as many odorous substances. This situation has advantages regarding the maintenance of indoor air quality.

The term odor control can mislead when applied to the use of a filter or other control device. Whereas the device may reduce the concentration of some contaminant by 90%, it will not necessarily reduce the contribution of that contaminant to the overall level by a commensurate amount. To understand a common disparity between efficacy of control of an odorant and efficacy of control of an odor requires knowledge of odor as a biological and perceptual response. A section on odor perception therefore serves as a companion to that on odor control. The section on perception will draw mainly from findings of the psychophysical laboratory, i.e., the laboratory devoted to quantification of sensory phenomena. Much of the research on ventilation requirements actually comprised applied psychophysics. The section on perception can possibly enlighten regarding such matters as why it is virtually impossible to ventilate a building at a high enough rate to eliminate unwanted odors entirely. As an example, Dravnieks (7) found that a tenfold dilution of tobacco smoke decreased its odor by only one-half. The finding of such a flat psychophysical (dose-response) function reveals that virtually unachievable rates of ventilation would be necessary to bring a moderate intensity of tobacco smoke odor to a just-detectable level.

The section on odor perception focuses strictly on sensory phenomena rather than on methodology. Methodology, both chemical and psychophysical, receives separate treatment in a section that just precedes the final section on prospects. In a way, it is unfortunate that the human psychophysical response must continue to serve as the primary means to decide the adequacy of ventilation. This implies, quite correctly, the absence of an odor-meter that can monitor all odor-relevant information in a space and can then deliver an appropriate amount of ventilation. Odor science has simply failed to mature to the point where the scores, hundreds or even thousands of organic materials present in the effluent of cooking, human bodies, or cigarette smoke can be sifted and transformed in such a way as to yield a numerical index of odor intensity or acceptability.

INVESTIGATIONS OF VENTILATION REQUIREMENTS

In a notable experiment reported in 1905, L. Paul shut a man in a chamber of high temperature, high humidity, and little ventilation (8). Although the occupant became very uncomfortable, persons who sat outside and breathed air from the chamber felt no discomfort. Conversely, the occupant of the hot, humid, and ill-ventilated chamber obtained no relief from the opportunity to breathe outside air. Hill and colleagues (9) offered similar observations that, like those of Paul, supported a cutaneous theory of ventilation requirements:

> In one class of experiments we shut within the chamber seven or eight students for about half an hour and observed the effect of the confined atmosphere on them. We kept them therein until the carbon dioxide reached 3 to 4 per cent. and the oxygen had fallen to from 17 to 16 per cent. The wet-bulb temperature rose meanwhile to about 26.6° to 29.5°C (80° to 85°F) and the dry-bulb a degree or two higher. The students went on chatting and laughing but by and by as the temperature rose they ceased to talk and their faces became flushed and moist. We watched them trying to light a cigarette (to relieve the monotony of the experiment) and puzzled by their matches going out, borrowing others, only in vain. They had not sensed the percentage of the diminution of oxygen, which fell below 17. Their breathing was slightly deepened by the high percentage of carbon dioxide, but no headache occurred in any of them from the short exposure to from 3 to 4 per cent. carbon dioxide. Their discomfort was relieved to an astonishing extent by putting on the electric fans placed on the roof.

Theories of ventilation spawned in the 19th century were predicated almost exclusively on control of one or another chemical contaminant. For instance, the influential European researcher, Pettenkofer, concluded that when air became odorous it probably contained unhealthful levels of contaminants from the bodies of occupants. On the assumption that readily measurable but relatively harmless carbon dioxide covaried closely with odor, Pettenkofer recommended ventilation rates that would keep carbon dioxide levels below 0.15%. Various influential Americans argued for much stricter control of carbon dioxide (0.06-0.08% maximum) and thereby began a tradition of excessive ventilation.

New York State Commission on Ventilation

The New York State Commission focused on the ventilation needs of students, both in field and laboratory experiments. Throughout almost eight years of data-acquisition under the leadership of C.-E. A. Winslow, the Commission explored the influence of ventilation on such diverse functions and indices as body temperature, comfort, appetite, rate of physical work, intellectual performance, motivation, respiration, metabolism, condition of the nasal mucosa, frequency of colds, blood pressure, hematocrit, and even the growth of experimental animals (10). The investigations relied upon objective indices (e.g., rate of work) whenever possible, but supplemented these with subjective indices (e.g., scales of discomfort, odor, warmth) when necessary. The studies implied that thermal characteristics of the air weighed far more heavily than chemical characteristics. That is, temperatures that departed only moderately from neutral would influence such indices as body temperature, feelings of comfort, and rate of work more readily than would high levels of carbon dioxide or other airborne substances.

Although there existed at the time no instruments to monitor the concentration of organic effluent from the human body, the Commission concerned itself with this effluent mainly through odor. In a two-year series of laboratory observations, the Commission found that poor ventilation impaired appetite. This conclusion emerged from hundreds of observations of food eaten in a temperature-controlled experimental chamber with occupants naive to conditions of ventilation. The effect, approximately equal to a 5% reduction in food consumed, seemed unaccompanied by any signs of physiological distress and even conscious discomfort. Nevertheless, the Commission expressed concern over the findings and sought to tie it into results on the rate of growth of guinea pigs reared in a rancid environment:

> ... it appears that the air of an unventilated room vitiated by human occupancy does contain substances which tend to diminish the appetite for food. In course of time this effect might prove of fundamental importance in relation to health, and it is therefore evident that, although the chief influences of the atmosphere are physical in nature, the indirect chemical effect of vitiated air cannot be wholly overlooked.... These results obtained with human subjects are confirmed by the demonstration that stronger organic odors produce a transient but quite definite check upon the rate of growth of guinea pigs. [p. 86]

Only one other index of performance, viz., amount of work (repetitive lifting) performed, supported a strong "chemical" component in the requirements for ventilation. In both cool (68F; 20C) and warm (75F; 24C) environments, subjects performed about 10% less work in an unventilated as in a well-ventilated space. (For comparison, the subjects performed about 15% less work in the warmer environment.) The Commission could never say with certainty whether these results, obtained in an experimental chamber, arose from odors, from organic contaminants, or from carbon dioxide. However, the investigators had decided from their review of prevailing knowledge that carbon dioxide, which occasionally rose to about 0.5% in the unventilated experimental chamber, held little practical danger:

> The oxygen may fall from 21 per cent to 20 per cent, and the carbon dioxide may rise from 0.03 to 0.5 per cent; greater changes than these are not observed even in the most crowded and worst ventilated room on account of the leakage through walls and ceiling and cracks of all sorts. Such values are very far from the values which are found to produce harmful physiological effects. The air in the lungs under normal conditions contains 16 per cent of oxygen and 5 per cent of carbon dioxide and the respiratory apparatus easily accommodates itself to considerable variations in the composition of the atmosphere by slight automatic changes in the rate and depth of respiration so as to maintain the composition of the alveolar air unchanged. [p. 5]

In the Commission's field studies, conducted in schools in such diverse locations as New York, Connecticut, Massachusetts, and Minnesota, the level of carbon dioxide never came close to 0.5%. This does not surprise since the field work focused on the adequacy of various types of commonly employed ventilation systems (e.g., window alone, window with gravity exhaust, plenum with fan). Even a poorly designed system tended to protect against a large buildup of carbon

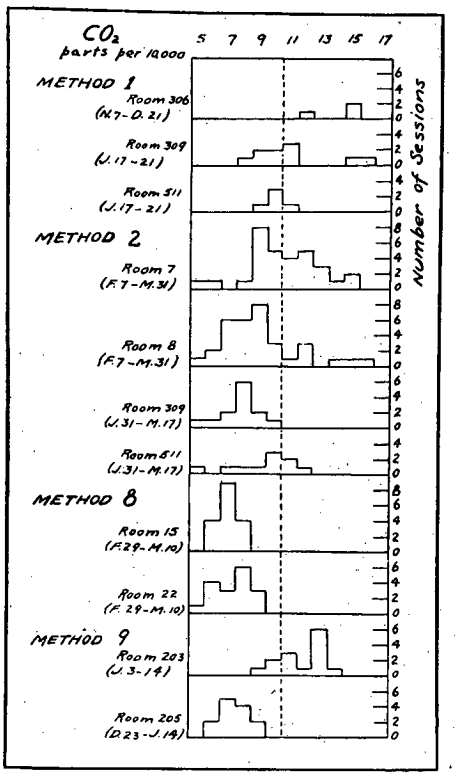


Fig. 1. Number of sessions in which an observer judged various classrooms to be free from odor vs. concentration of carbon dioxide. The methods listed at the left correspond to procedures of ventilation as follows: 1) window supply, no exhaust duct, 2) window supply, gravity exhaust, 8) plenum fan supply, gravity exhaust, and 9) plenum fan supply and exhaust. The observations led the N.Y. State Commission on Ventilation to conclude that any relation between concentration of carbon dioxide and odor would depend on the type of ventilation system employed. From N.Y. State Commission on Ventilation (10).

dioxide. Presumably these systems also provided reasonable control of organic contaminants. This situation therefore dampened any further concern with the influence of contaminants on appetite or ability to perform work, except insofar as normally encountered odor levels might mediate such effects. Concern with odorous contaminants led to the accumulation of observations on the co-variation of odor and carbon dioxide, depicted in Fig. 1 (see Table 3 for additional details). These judgments came from one or another worker in the field-team and therefore possess obvious limitations. The results implied that in general the presence of odors offers only a moderately reliable cue to the presence of other contaminants. The results also revealed that a criterion of no odor would lead to very high rates of ventilation. Reliance on such a criterion, invoked in the late 19th century in the name of avoiding mysterious human emanations then known variously as

Table 3

Summary of the Performance of Five Ventilation Systems in Classrooms (From N.Y. State Commission on Ventilation)

Method	1 Windows with no gravity exhaust	2 Windows with gravity exhaust	2 (D)* Windows, deflectors, gravity exhaust	9 Plenum with humidification, fan exhaust (fresh air)	9 Plenum with humidification, fan exhaust (re-circulated air)
Room Numbers	203, 205, 207, 208, 209, 211, 306, 309, 511	206, 306, 308†	207, 208, 209, 211, 309, 511	203, 205	203, 205
Number of sessions	487	223	729	205	201
Heat output of occupants B.t.u. per hour	14,600	14,500	12,500	16,700	16,200
Capacity per 100 B.t.u., cubic feet	66.0	68.0	77.0	56.0	58.0
Outdoor temperature, ° F	45°	41°	41°	41°	41°
" relative humidity, per cent	51	52	54	53	53
Indoor temperature, ° F	66.9°	66.3°	66.8°	67.9°	68.1°
" mean deviation from temperature average	1.7°	1.6°	1.8°	1.5°	1.6°
" relative humidity, per cent	30.7	29.8	28.4	38.1	38.7
Windows: Per cent. closed	3	11	4	99	99
" open top	51	86	27	1	1
" open bottom	85	9	89	0	0
Door, per cent. open	4	7	2	0	0
Observer's sensations: Per cent. odor	40	24	13	29	59
" marked odor	12	5	3	9	3
" especially fresh	23	36	56	4	10
" too warm	16	8	8	6	5
" too cool	3	8	4	2	5
" moist	1	1	0	10	12
" dry	9	10	8	1	0
" dead	9	6	5	9	24
" breezy	6	6	6	1	1
Teacher's sensations: Per cent. unfavorable air conditions	17	22	9	49	55
" too warm	15	11	5	24	34
" too cool	5	12	4	11	12
" moist	0	0	3	5	6
" dry	16	9	4	7	11
Carbon dioxide, parts per 10,000	8.6	8.5	8.3	8.7	10.9
Temperature: Below 65°	12	22	16	2	3
65°-70°	79	75	78	89	88
Above 70°	9	3	6	9	9

* 2, without window deflectors. 2 (D), with window deflectors.
† All three rooms have eastern exposure.

anthropotoxin, morbific matter, and crowd poison, had already led to the recommendation of 30 cfm (15 L/s) per pupil for schoolrooms (11). A suspicion that this recommendaton was far too high had led in part to the creation of the Commision. After it had completed its study, the Commission could confidently reject the recommendation as both unnecessary and wasteful of energy.

Table 3 shows how the odor impressions of the Commission's observer, who sought to evaluate a school room in the manner of a casual visitor, fitted into the physical and subjective profiles of ventilation systems. This table, based on almost 2000 sessions of data collection showed that a combination of apparent warmth and odor seemed to determine the acceptability of the air. Such data helped the Commission to decide that window ventilation with gravity exhaust, a relatively inexpensive way to ventilate, held great promise for the schools of that era. Before it reached that conclusion, however, the Commission also solicited judgments of odor, comfort, etc. from the students themselves, as well as from teachers and observers.

Squads of high school girls, blindfolded and naive to the variables under manipulation, entered various classrooms for 35 min and periodically judged odor,

Table 4

Subjective Impressions of High School Students Brought Blindfolded into Fan Ventilated and Window Ventilated Rooms. Entries: Percent of Total Votes (From N.Y. State Commission on Ventilation)

Percentage Summary of Sensation Votes

(Figures show per cent. of total votes)

Vote	Fan rooms	Window rooms
Odor:		
Present	14.7	9.6
Marked odor	1.4	0.9
Especially fresh	10.0	16.5
Temperature (beginning):		
Too cool or too cold	14.6	23.2
Satisfactory	67.0	68.7
Too warm or too hot	18.4	8.1
Temperature (end):		
Too cool or too cold	24.8	25.1
Satisfactory	64.2	67.3
Too warm or too hot	11.0	7.6
Stuffiness:		
None	73.4	87.2
Stuffy	9.6	3.3
Close	13.4	7.0
Stale	1.7	1.2
Dead	1.7	1.3
Air motion:		
Not apparent	67.6	68.6
Breeze	19.7	20.6
Drafts	12.7	10.8
Comfort:		
Comfortable	66.0	69.2
Uncomfortable	34.0	30.8

temperature, stuffiness, drafts, and general comfort. Judgments of odor, rendered 1 min after entry, followed the scale:

1. Exceptionally clean and sweet
2. Odor absent
3. Slight odor
4. Marked odor
5. Very unpleasant odor.

A total of almost 1,000 sets of judgments summarized in Table 4 led the Commission to favor the window-ventilated over fan-ventilated rooms under comparable conditions of temperature and ventilation rate. Nevertheless, the very slightly cooler conditions produced by window ventilation may have distorted the assessment of odor and stuffiness. Within the context of the study, this possibility only reinforced the Commission's conclusion that thermal factors weighed more heavily than chemical. Furthermore, any advantage of window over fan ventilation seemed secondary to the absence of a clear disadvantage to energy-saving and cost-saving window ventilation.

Attention to functional relations also characterized studies at Harvard School of Public Health. Lehmberg, Brandt, and Morse (15) of Harvard, who reported their results in the same year as Houghten and colleagues, recognized that

> Next to the thermal condition of the air as indicated by its temperature and humidity, the intensity of odor observed upon entering an occupied room from outside fresh air furnishes the most valuable evidence of good or bad ventilation.... The amount [of fresh air] needed varies so much under various conditions that it seemed advisable to study the problem first in the laboratory where the various factors can be controlled. [p. 158]

Their study, performed under contrived conditions, had general rather than specific implications for ventilation requirements. Details of the experiment included the following: A male subject would enter a small (17.7 cu ft; 0.5 m^3) box through which air could be flowed. An exhaust pipe that led from the box contained holes where observers could sniff the exiting air and rate it on the scale shown in Table 5. Rate of flow through the box varied from 1 to 50 cfm (0.5-25 L/s). The series of dilutions obtained in this manner permitted Lehmberg et al. to erect functions of the sort shown in Figs. 3 and 4. These reveal that body odor varied with body surface area and with ambient temperature, as well as with the amount of fresh air delivered to the box. Regarding any differences between the sensations of the occupant and the sensations of observers, Lehmberg and colleagues stated:

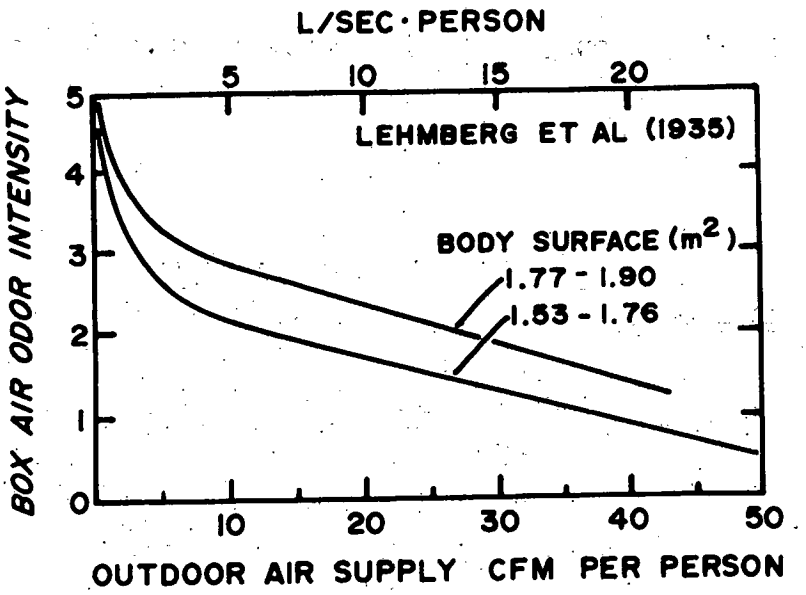


Fig. 3. Showing how odor intensity varied with fresh air supply to a small chamber containing a sedentary subject. Upper curve shows judgments of the odor generated by persons of relatively large surface area and lower curve shows judgments of the odor generated by persons of smaller surface area. Adapted from Lehmberg et al. (15).

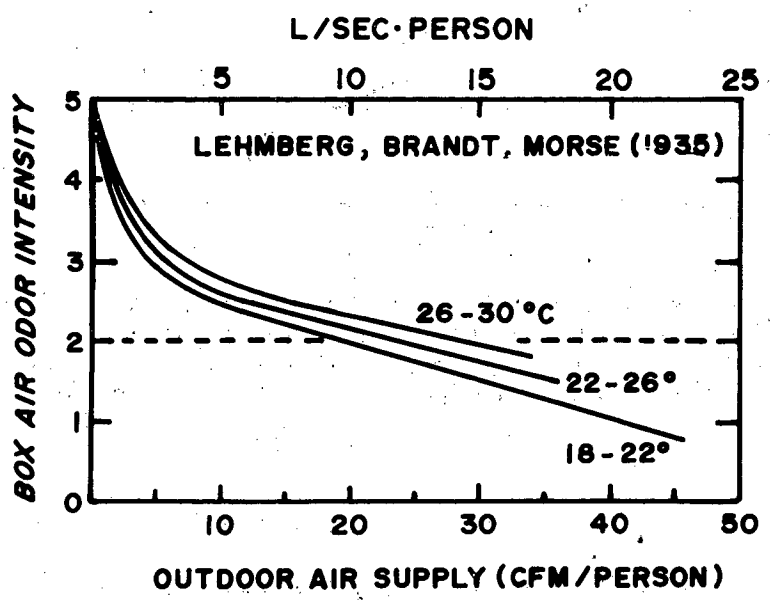


Fig. 4. Showing how odor intensity varied with fresh air supply to a small chamber containing a sedentary subject. The three different functions reveal the influence of the chamber's temperature on the odor intensity produced by the subject. Adapted from Lehmberg et al. (15).

> Despite the high odor intensities reported by the judges, who compared the fresh air going into the box with the used air coming out of the box, the subjects inside the box were as a rule unconscious of odor, owing to olfactory adaptation, except for a sensation of staleness, flatness, or lack of freshness in the air as perceived by the sense of smell. Such sensations constituted, in fact, the chief criterion of bad air in the opinion of the subjects. Complaints of this sort were most frequently associated with ventilation rates under 5 cfm even when the air was neither too warm nor too cool. A few of the subjects claimed to have actually smelled a weak body odor throughout the test period with ventilation rates up to about 10 cfm. [p. 162]

The rather high (≈ 20 cfm or 10 L/s) ventilation rate generally necessary to maintain the odor from Lehmberg's chamber at even a moderate level (as judged by observers rather than occupants) raised the question of how ventilation rate would vary with air space per person (or, with the inverse, occupation density). This question had previously received little attention, presumably because most earlier research had focused on ventilation requirements for classrooms, where air space per person generally equalled about 200-300 cu ft (5.6-8.5 m^3) per occupant. In

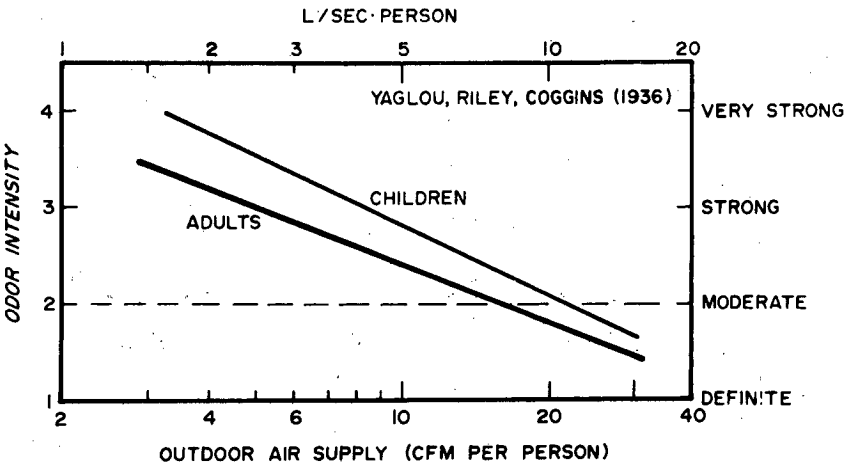


Fig. 5. Showing how odor intensity varied with fresh air supply when seven adults or children occupied a chamber of 1410 cu ft (39.5 m^3). Observers entered briefly from an odor free room. Adapted from Yaglou, Riley, & Coggins (17).

the discussion that followed Lehmberg's oral presentation at the Annual ASHVE meeting in 1935, Winslow articulated the issue in this fashion (16):

> Here, as I understand it, you have almost solely the dilution value of this 10 or 20 or 30 cu ft that passes through the box. Would it not be true that in a room where there was a considerable air space you would get another factor in the way of the dissipation and the gradual disappearance of those odors that would give you somewhat less odor with the same air change than you would get in a case of this kind? [p. 165]

Yaglou, Riley, and Coggins, improving upon the earlier experiments of Lehmberg and associates, placed from 3 to 14 subjects into a moderate-sized chamber (1410 cu ft; 39.5 m^3) and asked observers to enter briefly and to rate the odor under various conditions of ventilation (17). Commonly the air supply to the room equalled 30 cfm (15 L/s) per occupant, all or part of which could comprise outdoor air. Odor intensity, judged on the scale shown in Table 5, varied logarithmically with outdoor air supply per person for any given number of persons. This held true for both children (7-14 yrs) and adults. Nevertheless, children emitted stronger odors than adults (see Fig. 5), despite a smaller body surface area. For both adults and children, the amount of ventilation air needed to maintain odor at any given level increased disproportionately with the density of occupation in the chamber. For instance, occupation by three adults or three children required approximately 21 cfm (10.5 L/s) and 33 cfm (16.5 L/s), respectively, in order to maintain odor at a moderate level. Occupation by seven adults or seven children required approximately 112 cfm (56 L/s) and 147 cfm (73.5 L/s), respectively. Hence, ventilation rate <u>per occupant</u> increased with density of occupation. Figure 6 shows the psychophysical functions that would permit, by interpolation if necessary, calculation of ventilation requirements for adult occupants in spaces ranging from highly crowded, 100 cu ft (2.8 m^3) per occupant, to rather uncrowded, 500 cu ft (14 m^3) per occupant. Many indoor

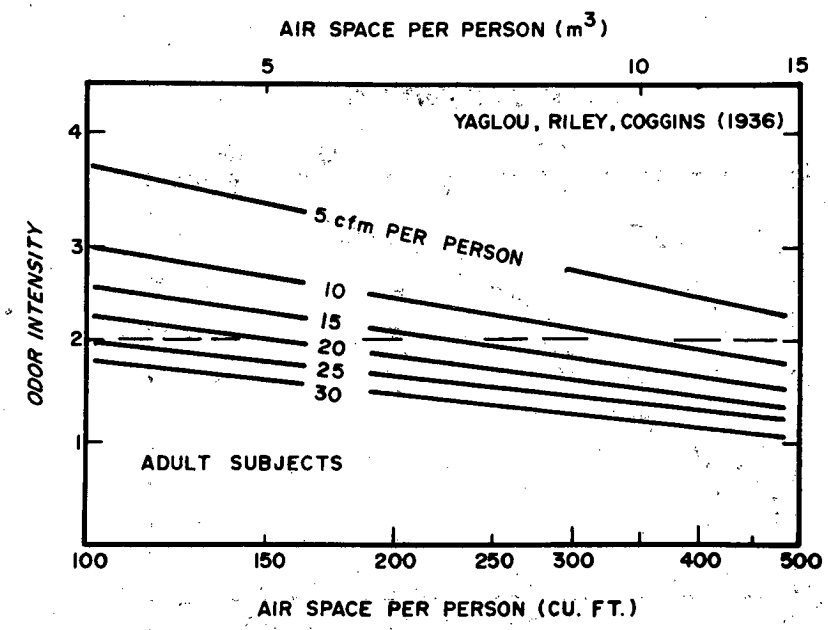


Fig. 6. Showing how odor intensity in the experimental chamber varied with air space per person with rates of fresh air supply from 5 - 30 cfm (2.5-15 L/s). Adapted from Yaglou, Riley, & Coggins (17).

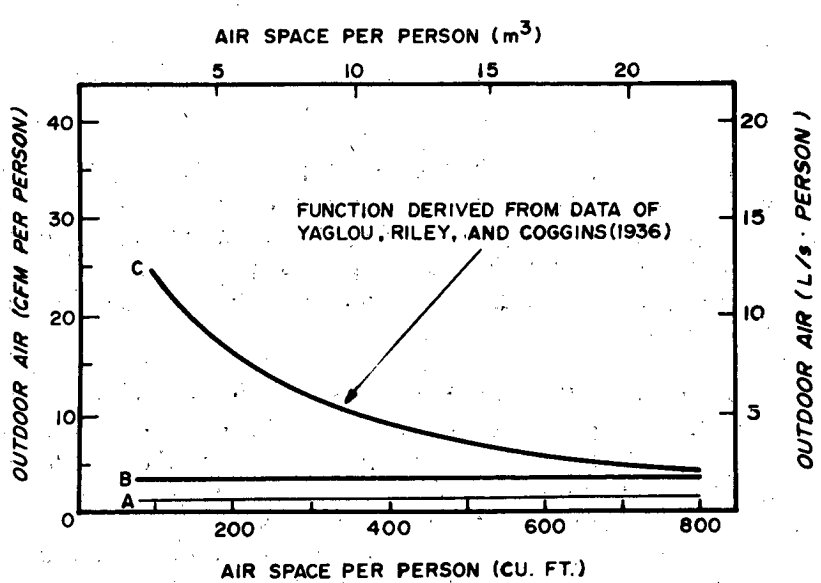


Fig. 7. Relation between ventilation rate and air space per person according to three criteria: A, maintenance of oxygen; B, control of carbon dioxide to a level of 0.6%; C, control of body odor at a moderate level under sedentary conditions of occupancy, no smoking. Function for body odor was erected from judgments of observers who briefly entered a chamber occupied by persons of normal hygiene for up to 3.5 hrs.

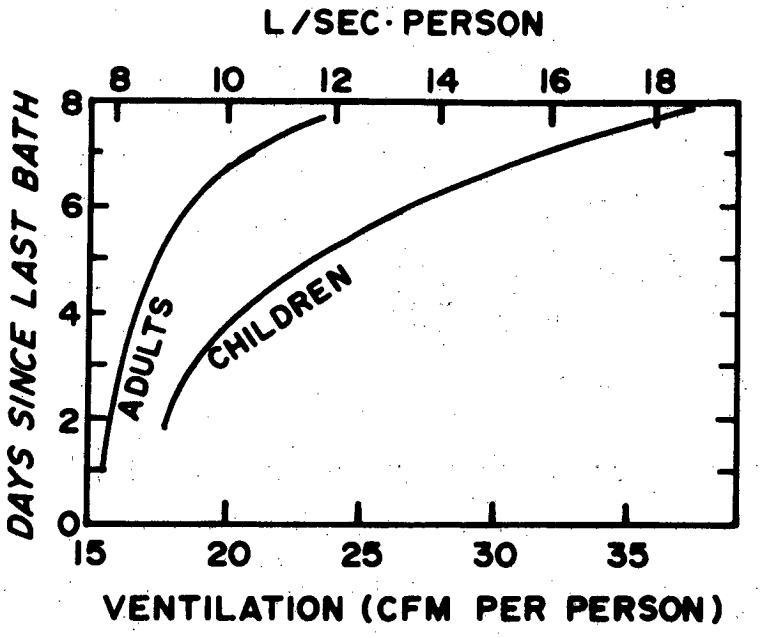


Fig. 8. Influence of personal hygiene (days since last bath) on ventilation requirements for adults and grade-school children. Ventilation requirements decided on the basis of outdoor air required to maintain odor at moderate on the scale in Table 5. Adapted from Yaglou, Riley, & Coggins (17).

spaces actually offer more air space than 500 cu ft (14 m^3) per occupant and, as Winslow had anticipated, these spaces require only trivial amount of ventilation for purposes of odor control. The function relating ventilation requirements (derived from Fig. 6)to air space per person appears in Fig. 7. This function essentially summarizes Yaglou's recommendations and has provided the underpinnings of various ventilation standards and codes (18).

Blind adherence to recommendations based exclusively on control of body odor from normal persons has relatively little justification. Indeed, Yaglou and associates took pains to point out that personal hygiene alone could exert a powerful influence on ventilation requirements. Fig. 8 illustrates this influence, an influence that allowed the authors to make yet another point, viz., that personal habits would vary enough to weaken any relation between odor intensity and concentration of CO_2. In their view: "a great deal of unjustified effort would be saved by discontinuing the usual measurements of CO_2 in ordinary ventilation work, except perhaps in instances in which the airflow is well under 10 cfm per person" (p. 155).

These and other considerations, such as the presence of odorous contaminants other than body odor in indoor spaces, have conspired to push ventilation rates above those recommended by Yaglou. A contaminant such as tobacco smoke odor may

prove so dominant that it dwarfs the contribution of other odorous contaminants. Yaglou addressed this problem two decades after his initial research (19). Shortly after the first study, however, Yaglou in collaboration with Witheridge inquired into whether body odor behaved like a typical odorous contaminant (20). Much to their consternation it did not:

> 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]

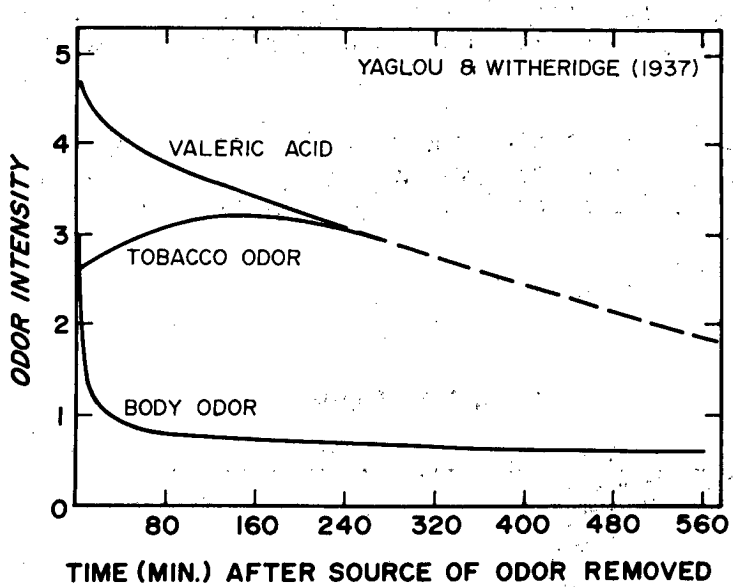


Fig. 9. Showing how odor decayed in still air in a chamber after (a) an open flask of valeric acid had been removed, (b) five cigarettes had been smoked, (c) previous occupants (nonsmoking) had left the chamber (function labeled body odor). Observers entered the unventilated chamber periodically in order to rate intensity. The function for body odor decayed in approximately the same manner in "four experiments carried out under representative conditions in winter and summer with respect to temperature, humidity, clothing, and other factors" (p. 424). Data from Yaglou & Witheridge (20).

This conclusion arose from results like those depicted in Fig. 9 which shows how odor declined in the still air of an unventilated chamber after removal of the source of odor. Body odor decayed abruptly from very strong to definite within 4 min after occupants left the chamber. By contrast, the odor of valeric acid

decayed to definite only after a number of hours. Indeed, body odor decayed far more rapidly than the highly reactive substance ozone. The peculiar behavior of body odor even prompted the conclusion (20): "The influence of per capita air space on ventilation requirements from the standpoint of body odor would, therefore, seem to be explainable, almost entirely, by the rapid disappearance of body odor" (p. 425). In essence, this statement disclaimed the general usefulness of Yaglou's recommendations in Fig. 7.

According to Yaglou and Witheridge, the other odors they studied (valeric and butyric acid, tobacco smoke, and ozone) were all capable of masking body odor completely. This presumably meant that each might generate its own "ventilation requirements function" of different shape and level than the curve in Fig. 7. This would seem particularly true of tobacco smoke odor. As Fig. 9 shows, in an unventilated chamber, tobacco smoke odor actually increased for approximately 3 hours after cigarettes were removed. Hence, whereas the control of body odor seemed accomplished most easily in a large room with low air flow, the control of tobacco smoke odor would seem accomplished more easily in small rooms with fast ventilation. The chemical or physical changes responsible for the enhancement of tobacco smoke odor and the decay of body odor remain unstudied. Although the issue will undoubtedly defy simple analysis, the technical means for the analysis (e.g., gas chromatography/mass spectrometry) now exist.

Yaglou subsequently documented the need for large amounts of ventilation air under conditions of cigarette smoking (19). Fig. 10 reveals that visitors who entered from odorless air required a ventilation rate of roughly 40 cfm (20 L/s)

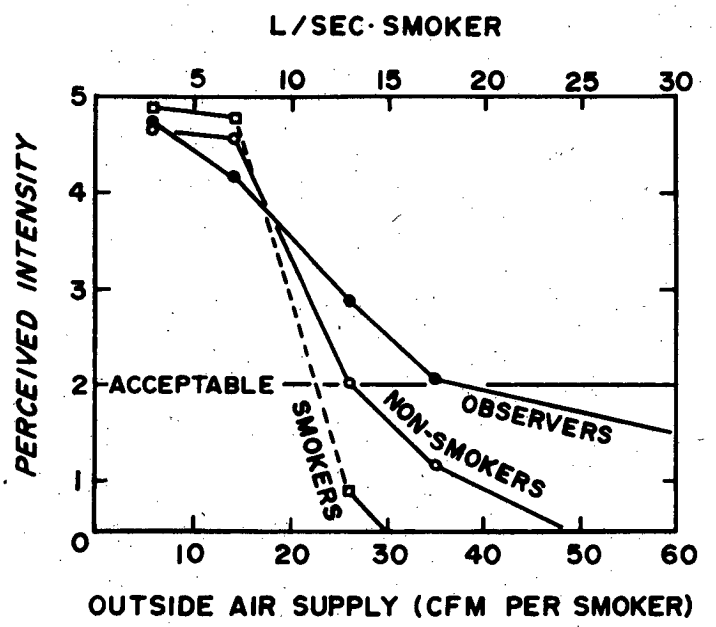


Fig. 10. Showing how odor intensity varied with fresh air supply when 9 persons, including 6 smokers, occupied Yaglou's chamber and smoked cigarettes at a rate of 24 per hr. Functions labeled smokers and nonsmokers depicts judgments of occupants. Function labeled observers depict judgments of persons who entered briefly from an odor-free room. Adapted from Yaglou (19).

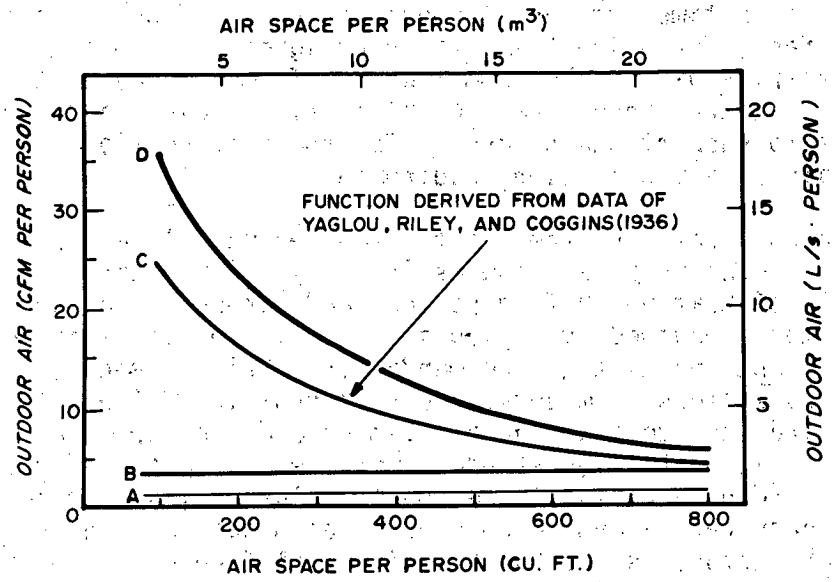


Fig. 11. Same as Fig. 7, but with an additional function (D) to represent the ventilation requirements for smoking or some physical activity. Curve D, a 50% upward transposition of curve C, has seen some use even though it has no experimental basis.

per smoker for an acceptable environment. This requirement occurred under conditions where 24 cigarettes, 4 per smoker, were smoked per hour in the same chamber used to study body odor two decades earlier. The high rate of smoking led to approximately intolerable odor and irritation under ventilation conditions deemed adequate for nonsmoking occupancy. Yaglou investigated only one rate of smoking and hence could not recommend a complete set of ventilation requirements, as he had for control of body odor.

Cigarette smoking causes more serious problems than any other contaminant for ordinary ventilation systems (21). Irrespective of whether there existed data on the matter, there existed a need to recommend ventilation rates for spaces where smoking normally occurred (22). In the absence of solid data, it was recommended that smoking areas should be ventilated at rates 50% higher than needed to control odors from nonsmoking occupants. Figure 11 depicts the "ventilation requirements" for spaces where no smoking occurs and for spaces where smoking or moderate physical activity occurs. The need to make a determination on the basis of little data was hardly new in the field of ventilation engineering. At the end of Yaglou, Riley and Coggins's paper on ventilation requirements for nonsmoking occupants, W. H. Driscoll had observed (23):

> When we (the Ventilation Standards Committee of the American Society of Heating and Ventilating Engineers) finally decided that we would take 10 cfm per person as the minimum it was a sheer compromise, merely an attempt to finish the work of the Committee and get the report before the Society. There was a difference of

> opinion as to whether the 30 cu ft that have been set up as a standard since time immemorial should be adopted, or whether no cubic feet, for which there was very agressive support, not necessarily within the Committee but from outside of the Committee, on the theory that no scientific studies had ever been made to support the necessity for the introduction of any outdoor air as a ventilation requirement. [p. 160]

Except for Yaglou's results, the dearth of experimental data on ventilation requirements remains about as severe now as in the 1930's. Standard 62-73 of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers contains two refinements endowed by Yaglou's data: 1) specification of ventilation rate per occupant and 2) the recommendation of higher ventilation rates per occupant under conditions of moderate to high crowding. The rates recommended in the ASHRAE standard seem to take the activities and the tolerance of occupants implicitly into account. The standard considers almost every conceivable type of indoor space (dining rooms, ticket booths, lavatories, auditoriums, dry cleaning establishments, etc.) and recommends in each case a rate that presumably gives weight to such factors as whether and with what frequency smoking will occur. The data points in Fig. 12 illustrate recommended rates for a large variety of spaces versus the estimated air space per person. The function that falls below the bulk of the points represents Yaglou's recommendations. Even though the points show considerable scatter, as indeed they should, they follow roughly the curvature of Yaglou's recommendations. Those recommendations, predicated on the control of body odor alone, seem to form a lower boundary for the consensus recommendations in ASHRAE Standard 62-73. This is not the case in ASHRAE 90-75 (Standard for Energy Conservation in New Building Design). Here, the consensus values, reduced on the average 30% below the midpoint of the recommended intervals of ASHRAE Standard 62-73, cluster around the function derived from Yaglou's data, data that have exerted remarkable leverage mainly by default.

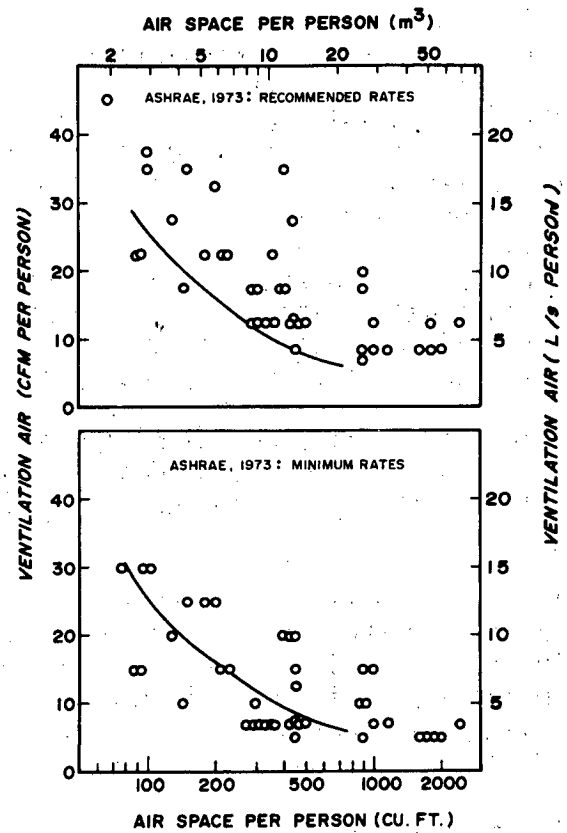


Fig. 12. Top: Points depict rates of ventilation recommended for various residential and commercial spaces by ASHRAE Standard 62-73 versus air space per person (logarithmic scale). Air space per person was derived from estimates of occupancy per 1000 sq ft (93 m^2) of floor area (incorporated into the standard) and from the present authors' estimate of ceiling height. Excluded were spaces, such as theaters, where ceiling height might vary considerably from one space to another. Bottom: Points depict rates of ventilation recommended for new buildings by ASHRAE Standard 90-75. The points comprise the so-called minimum ventilation rates of Standard 62-73. The line in both top and bottom portions is function C from Fig. 7.

ODOR CONTROL

The air supplied to a room by means of a mechanical ventilation system generally contains a mixture of outdoor air (ventilation air) and air previously circulated through that space (recirculated air). This mixture of ventilation and recirculated air generally serves to maintain comfortable thermal conditions as it simultaneously dilutes contaminants. Ever since mechanical ventilation systems have become available, engineers have seen the economic benefits of high rates of recirculation (24). They have also recognized the penalty for increased reliance on recirculation: an increase in odor level and in inodorous contaminants. Various means to treat recirculated air can remove a broad range of contaminants and can enhance the attractiveness of recirculation. ASHRAE Standard 62-73 acknowledges the benefits of such treatment:

> If, in addition, high efficient adsorption or other odor and gas removal equipment is employed ... the outdoor air requirement may be reduced to 15% of the specified required ventilation air quantity. [p. 5]

The means now available to eliminate contaminants in the indoor air differ little from the means available over the last two to three decades. No generally available method will eliminate carbon dioxide, but certain well known methods will eliminate the organic materials that, in small concentrations, generally give rise to indoor odors. The primary method of choice involves adsorption of contaminant on activated charcoal.

Deodorization of Recirculated Air by Granular Media

The general principles that determine the relative economic advantages of ventilation by outdoor air or by recirculated indoor air deodorized by activated carbon have long been understood (25). Briefly, the economic choice is between the cost of primary equipment for conditioning outdoor air plus the operating cost imposed by the outdoor air load, as against equipment and operating cost of deodorizing an equivalent volume of already conditioned indoor air. Even during the "cheap energy" years of the 1950s, the cost comparisons indicated an overwhelming advantage for activated carbon. Table 6 reproduces both a typical cost analysis of that period and an updated version. The earlier set of calculations naturally led to the expectation that the use of activated carbon systems for purifying ventilation air would become very widespread.

The optimistic predictions for activated carbon in ventilating systems have been only incompletely realized. Since the rising cost of energy would tend to make the calculations of the 1950's conservative, one must look to other factors to explain the discrepancy. The various assumptions of "air conservation" must therefore be reexamined, and new studies must be undertaken to resolve some persistent technical uncertainties.

The following sections will summarize technical aspects of purification of ventilation air by activated carbon or other adsorbents. Certain practical problems inherent in the use of adsorbents will receive attention in the section denoted Summary and Prospects.

Table 6

Cost Analysis Showing the Benefits of Using Activated Carbon and Recirculated Ventilation Air. All Costs Are for 1000 cfm (500 L/s).

PRIMARY COST	1950s	1979
Activated carbon equipment installed	$170.00	$340.00
OPERATING COST PER ANNUM		
Carbon reactivation service (total, per reactivation)	$ 35.00	$ 85.00
COMPARATIVE OPERATING COSTS OF HEATING AND AIR CONDITIONING*		
Power, 1560 kWh		
at 0.015	$ 23.40	
at 0.033		$ 51.48
Fuel, 1400 gal		
at 0.08	$112.00	
at 0.57		$798.00
Estimated pumping and water cost	$ 10.60	$ 23.32
Total	$146.00	$872.80
CALCULATED SAVINGS FROM USE OF ACTIVATED CARBON, PER ANNUM		
$146 - $35	$111.00	
$872.80 - $85.00		$787.80

*Calculations of power and fuel consumption are from AIR CONSERVATION ENGINEERING, by H. Sleik and A. Turk, Connor Engineering Corp., Danbury, CT, 1953. The calculations assume year-round operation in mean temperature zone (approx. 5300 heating degree-days, 1200 cooling degree-days) and exclude cost of any additional fan-power needed in a carbon-containing HVAC system.

Activated Carbon

Activated carbon functions by the process of physical adsorption, which is the adherence of fluid matter on to the surface of a solid (26). In ventilation systems, the "fluid matter" is the gaseous, odorous components of the air. Practical adsorbents must have extensive surface areas per unit mass or volume of the solid and must also offer minimal resistance to the passage of air through them. These objectives are attained by the use of cylindrical or irregularly

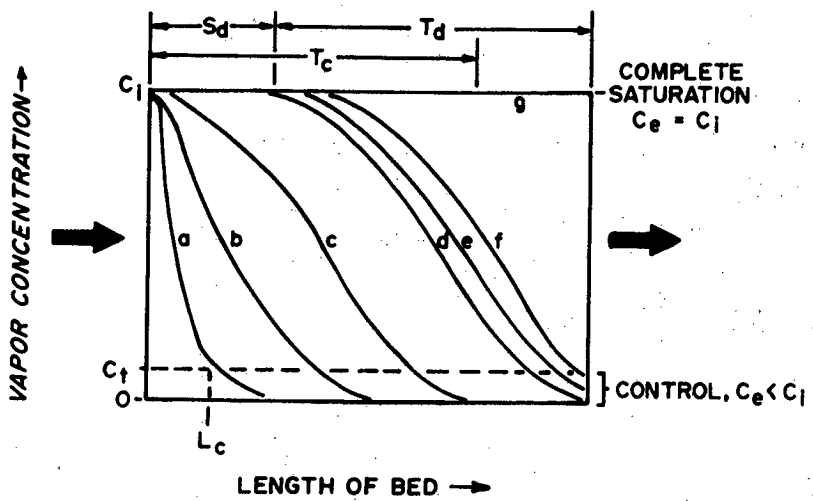


Fig. 13. Illustrating how an adsorbent bed would alter the concentration of a hypothetical contaminant contained within a moving air stream. Curves a through f show concentration (C) along the length of the bed. Curve a shows concentration at an early point in time; curve b at a later time, etc. See text for explanation of critical bed length (L_c), transfer zone (T), and saturation zone (S).

shaped granules whose largest dimensions range from about 2 to 3 mm (6-14 mesh Tyler Sieve Series), and which are extensively interlaced with pores of submicroscopic diameters. Under these conditions, the distances that individual molecules in the air stream must travel to reach some point on the surface is small and the transfer rate is therefore high. In practice, the half-life of airborne molecules streaming through a packed adsorbent bed is of the order of 0.01 second, which means that a 95% removal can occur in about four half-lives, or around 0.04 seconds (27).

Adsorbed matter may also condense in the submicroscopic pores of an adsorbent; this phenomenon is called capillary condensation. Such condensation accounts for a large proportion of the deodorizing capacity of the carbon.

The action of an adsorbent bed on a moving airstream is illustrated by the series of curves of Fig. 13. Curve a shows the vapor concentration within the bed shortly after the start of the adsorption process. (The bed is fresh.) The inlet concentration of contaminant is C_i. This level drops off sharply with increasing distance through the bed, and reaches "zero" after some finite distance.

(Theoretically, zero is never reached, but we assume that a nondetectable concentration is a practical "zero.") Let us assume that the objective of the process is to reduce C_i to some target concentration C_t which may be an odor threshold level, or perhaps some arbitrary fraction of C_i. The minimum bed thickness that could achieve this objective initially is called the critical bed depth, designated L_c in Figure 13. As time goes on and adsorption continues, the upstream portion of the bed becomes partly saturated and the vapor therefore penetrates more deeply, as shown in curve b. Finally the upstream section of adsorbent becomes completely saturated (curve c). The section of bed between saturation and "zero" concentration is the region in which adsorption is taking place, or the mass transfer zone. At the time the system has reached the condition of curve c, the length of this transfer zone is T_c. Now, as adsorption continues further, the transfer zone progresses downstream, but its length remains the same. Thus, when the system has reached the condition of curve d, the length of the transfer zone T_d is the same as it was before, but it is displaced to the right. The upstream section of the bed S_d is now saturated and inactive. We see now that as the curve continues to advance, C_e becomes greater than zero (curve e), and will reach the target concentration (curve f) long before the entire bed is saturated. Complete saturation ($C_e = C_i$) is represented by curve g. The entire pattern of moving curves is called the "adsorption wave."

Typical specifications for activated carbon to be used for air purification are given in Table 7.

Table 7

Typical Specifications for Activated Carbon Used for Air Purification

Property	Specification
Activity for CCl_4[a]	At least 50%
Retentivity for CCl_4[b]	At least 30%
Apparent density	At least 0.4 gm/ml
Hardness (ball abrasion)[c]	At least 80%
Mesh distribution	6-14 range (Tyler Sieve Series)

[a]Maximum saturation of carbon, at 20°C and 760 torr in an airstream equilibrated with CCl_4 at 0°C.

[b]Maximum weight of adsorbed CCl_4 retained by carbon exposure to pure air at 20°C and 760 torr.

[c]Percent of 6-8 mesh carbon which remains on a 14-mesh screen after shaking with 30 steel balls of 0.25-0.37 in. (0.635-0940 cm) diam. per 50 gm carbon, for 30 minutes in a vibrating or tapping machine.

Other Granular Media

Various other methods for deodorizing ventilation air by granular solid media at ambient temperatures have been suggested or might be considered. These alternatives may be categorized as follows:

(a) Oxygenated adsorbents vs activated carbon. Oxygenated adsorbents comprise the silica gels, fuller's, diatomaceous, and other siliceous earths, and synthetic zeolites or "molecular sieves." They also include metallic oxides, notably Al_2O_3. All of these materials have strongly polar molecular structures, because oxygen is much more electrophilic than silicon or aluminum (or, in fact, than any metal or semimetal). These adsorbents therefore show overwhelmingly greater preference for polar than for nonpolar molecules. As a result, if they are used with ventilation air, which is never completely dry, they become rapidly saturated with water, after which they are ineffective for deodorization.

Activated carbon, on the other hand, has an essentially non-polar molecular structure. Water vapor that is adsorbed by activated carbon from a moist air stream is gradually displaced by adsorbed organic vapors. This exchange is illustrated by Fig. 14, which is taken from a study of the saturation of activated carbon in an apple storage atmosphere at 85% relative humidity and 35F (1.5C), shows how the initially adsorbed moisture is gradually displaced by the adsorbed organic

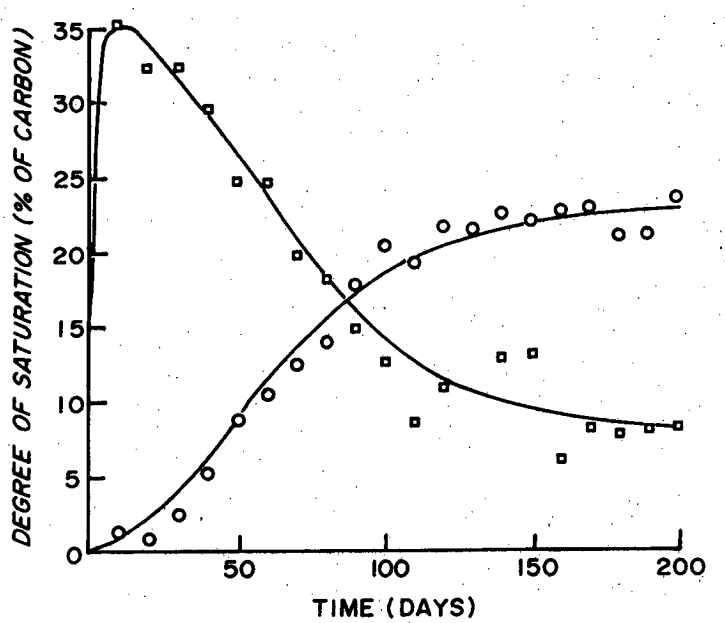


Fig. 14. Showing relative degrees of saturation of coconut shell activated carbon when challenged by air containing water vapor (x's represent adsorbed water) and organic vapors (o's represent adsorbed organics) in a commercial apple storage facility.

vapors (28). Note that the carbon initially adsorbs over one third of its weight of water, but that this quantity is gradually reduced as it is displaced by the organic vapors from the fruit, the total mass of adsorbed matter (water plus organics) remaining approximately constant.

Table 8 shows ranges of surface areas and pore volumes for several different adsorbents. Among these, activated carbon is generally highest in surface area and pore volume, the properties which primarily determine overall adsorptive capacity.

Table 8

Surface Areas and Pore Sizes of Adsorbents

	Activated carbon	Activated alumina	Silica gel	Molecular sieve
Surface area (m^2/gm)	1100-1600	210-360	750	
Surface area (m^2/cm^3)	300-560	210-320	520	
Pore volume (cm^3/gm)	0.80-1.20	0.29-0.37	0.40	0.27-0.38
Pore volume (cm^3/cm^3)	0.40-0.42	0.29-0.33	0.28	0.22-0.30
Mean pore diameter (Å)	15-20[a]	18-20	22	3-9

[a]Refers to micropore volume (< 25 Å diameter); macropores (> 25 Å) not included.

(b) Other non-polar adsorbents. Various synthetic organic polymers, such as polystyrene, have been used as adsorbents or solid phases in gas chromatography. These materials are less strongly retentive of organic vapors and therefore are more easily regenerated than is activated carbon. However, they are so much more expensive that for this reason alone they cannot be considered as practical alternatives for use in ventilation systems.

(c) Adsorbent impregnations. Adsorbents may react chemically with each other or with atmospheric oxygen. The adsorbent, by serving as a concentrating medium, speeds up the reaction rate. Material in the adsorbed state may be especially reactive; the adsorbent then functions as a true catalyst. In some cases a specially selected catalyst or reactant is incorporated into an adsorbent prior to the use of the adsorbent as an air purifier. The adsorbent is then said to be impregnated with the material. Such impregnation may increase the rate, capacity, or selectivity of the adsorbent for air purification.

For practical deodorizing applications, chemical reaction of a contaminant with a reactive impregnant is a mixed blessing. The irreversibility associated with chemical reactions is advantageous and in some cases so is the selectivity. But the total capacity of the adsorbent for nonselective retention of gaseous contaminants is reduced by these effects, and in most cases this reduction is an overriding disadvantage.

Permanganated alumina has been particularly recommended as a medium that combines the advantages of physical adsorption by the alumina with irreversible oxidation by the permangate (29, 30). Direct competition experiments in which equivalent beds of activated carbon and permanganted alumina were exposed to the same odorized air streams demonstrated that the carbon acted much more rapidly with the specific contaminants tested (31). However, no reliable comparative study using ventilation air has been reported.

Activated carbon in ventilation systems often adsorbs considerable quantities of SO_2 during the course of saturation. It would be advantageous to remove such matter irreversibly before the carbon is exposed to it, so that carbon loading can be restricted to odorous matter and the carbon service life between replacements can be extended. A suitable agent for this function is alkalized alumina. A process has been described (32) by which such impregnated alumina can be conveniently regenerated in place without interrupting the ventilation system.

Alternatives to Granular Media

Various air cleaning devices incorporated into ventilation or air conditioning systems might reduce odor levels in schools or hospitals. Most of these are already used in hospitals. For example, the University of Connecticut Medical Center, built in 1972, represents a state-of-the-art ventilation/air conditioning system. The systems serving the surgical areas and wards provide 100% fresh air. The components of the systems include:

1. roughing filter
2. spray washer
3. air conditioning unit (cooling coils)
4. heater (electrical)
5. oil filter
6. high-efficiency filter (baghouse)
7. humidification unit involving steam injection which adjusts relative humidity to 70% in air supplied to operating rooms.

The ventilation systems of schools commonly have no air cleaning components that could serve as odor control devices.

One possible odor control alternative is spray washing, intended primarily as a means to humidity or dehumidity air. It can remove odorous compounds soluble in water. Through the addition of chemicals such as caustic soda, glycol, salts, or oil the process may be adapted to remove acidic gases or various other contaminants (33). Successful elimination of air contaminants requires removal or regeneration of the liquid medium in the air washer. Without special attention to this matter, the air washer itself may create odor via evaporation of previously absorbed odorants or via the growth of mold or bacteria on the baffles of the washer. Condensation on air conditioning cooling coils provides a similar, if

often unintentional means of odor removal. The condensation process can remove both water vapor and the odorous vapors. Like spray washing, condensation on coils may also create odor.

Another alternative is nongranular filtration, including the use of electronic air cleaners. The electronic devices use a principle of electrostatic precipitation to collect particulate matter. The major limitation for odor control is that these air cleaners will only remove odorants conjoined with particulate matter. When tobacco smoke forms the primary contaminant in a space, removal of particulate matter may aid considerably in odor control (22). This matter awaits thorough exploration.

The final option considered here is control by odor modification. In this process, perception of an objectionable odor is eliminated through addition of an airborne substance intended to diminish odor intensity and to produce a pleasant sensation (34). This procedure increases the number of chemical substances in the air and seems to have little legitimate use in ventilation. Possible exceptions to such a proscription may occur under two circumstances: 1) unanticipated episodes of malodorous emissions, as from fires, may justify temporary use of odor modifiers, and 2) chronically and intractably odorous spaces occupied on a transient basis, such as the smoking cars of railroads, may present no economical alternative to odor modification.

ODOR PERCEPTION

Up to this point, we have ignored details of olfactory functioning. In a retrospective view of ventilation and odor control, such details have some importance (see particularly sections below on common chemical sense and on physical factors). In a prospective view, the details grow in importance. They make it possible to shape subsequent research and to anticipate the simplicities or complexities of various experimental outcomes.

The olfactory response shares common characteristics with other biological responses, particularly those to chemical stimuli. For instance, olfaction responds nonuniformly to stimuli: one stimulus may evoke a response at a level many orders of magnitude higher or lower than another. Olfaction responds nonlinearly: odor magnitude increases in a nonproportional fashion with stimulus magnitude. Olfaction displays interactive effects: odorous mixtures do not produce a perceived intensity equal to the simple sum of the unmixed components. Olfaction exhibits lability: odor intensity, quality, and acceptability all vary with prior conditions of stimulation, with time, and even in part with context. All of these factors play a part in odor measurement and control.

Nonuniformity

Commonly occurring odorous contaminants, such as body odor, contain many chemical constituents, some odor-relevant and some not (35). In any occupied space, body effluvia will add their presence to existing background substances. Figure 15 illustrates the kind of complexity seen in samples of indoor air analyzed

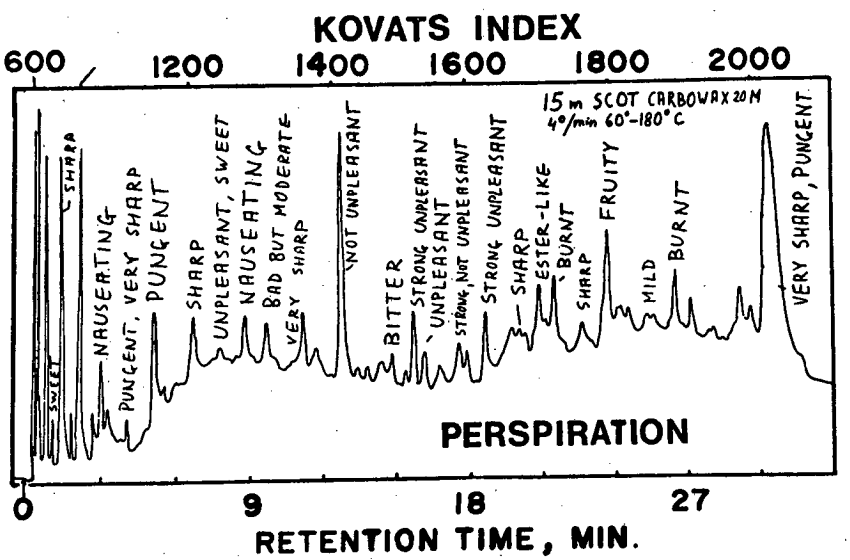


Fig. 15. An odor-annotated gas chromatogram, called an odorogram, of perspiration vapor. The annotations refer to the odor qualities noted by any observer when the various peaks eluted from the chromatographic column. The Kovats Index helps to identify the various substances. Adapted from Dravnieks (39).

chromatographically. The complexity, i.e., the number of substances detected, increases with the sensitivity of the measuring instrument. Because the nose can exhibit a sensitivity that rivals or exceeds the best instruments, samples collected for odor relevance invite a complex analytical outcome. Nevertheless, many constituents in a sample of indoor air may contain virtually no olfactory impact.

Instruments such as light meters and sound meters contain electronic networks tuned to weight individual frequencies according to sensory effectiveness. In the absence of known physicochemical correlates of olfactory effectiveness, analogous instrumentation does not exist for complex odorants. This situation leads to reliance on tables of threshold concentrations, such as Table 9 (36). This reveals large differences in olfactory effectivensss from one odorant to another. The complete table of 103 substances also reveals, at least to a reader sophisticated in chemistry, the absence of any superficially evident relation between physical or chemical properties and odor potency. Such tables (37, 38) may, however, give some idea of whether a substance found in a particular air sample could contribute to overall odor.

Table 9

Odor Threshold and Quality of Various Petrochemicals[a]

Compound	Absolute ppm	50% Recognition ppm	100% Recognition ppm	Quality
Acetone	20.0	32.5	140	Sweet/Fruity
2-6-Butanol	0.30	1.0	2.0	Rancid/Sweet
Ci-N-butylamine	0.08	0.27	0.48	Fishy/Amine
Diethylamine	0.02	0.06	0.06	Musty/Fishy/Amine
Ethul acetate	6.3	13.2	13.2	Sweet/Ester
Ethyl acrylate	0.0002	0.00030	0.00036	Sour/Pungent
Ethylene	260	400	700	Olefinic
N-Ethyl morpholine	0.08	0.25	0.25	Ammoniacal
Isobutyl acetate	0.35	0.50	0.50	Sweet/Ester
Isobutyl acrylate	0.002	0.009	0.012	Sweet/Musty
Methanol	4.26	53.3	53.3	Sour/Sharp
Methyl ethyl ketone	2.0	5.5	6.0	Sweet/Sharp
2-Methyl-5-ethyl pyridine	0.006	0.008	0.010	Sour/Pungent
2,4-Pentanedione	0.01	0.020	0.024	Sour/Rancid
Propionic acid	0.028	0.034	0.034	Sour
Propylene	22.5	67.6	67.6	Sharp/Amine
Propionaldehyde	0.009	0.040	0.080	Sweet/Ester

[a]Data from Hellman and Small (36).

Nonlinearity

Once above the level of detectability, perceived odor magnitude (ψ) generally grows as a power function of concentration (ϕ), i.e., $\psi = k\phi^{\beta}$, where β characteristically falls below 1.0 (40). The value of β actually varies substantially from odorant to odorant ranging from a low of about 0.1 to a high of about 0.7 (Fig. 16). A β of 0.7 implies that a tenfold change in concentration will cause a fivefold change in perceived odor magnitude, whereas a β of 0.1 implies that a tenfold change in concentration will cause merely a 50% change in perceived odor magnitude. The properties responsible for this variation in rate of growth remain only poorly specified. Most complex mixtures of odorous materials, such as the mixtures responsible for body odor and tobacco odor, probably contain some substances that would in isolation produce high values of β and some that would produce low values. Experiments on complex effluents from industrial operations have produced values close to 0.50 (41,42). This seems a good approximation to the modal value that might occur in a battery of stimuli chosen randomly. Body and tobacco odor may conform similarly to a square root function (β = 0.5), but this remains an open question.

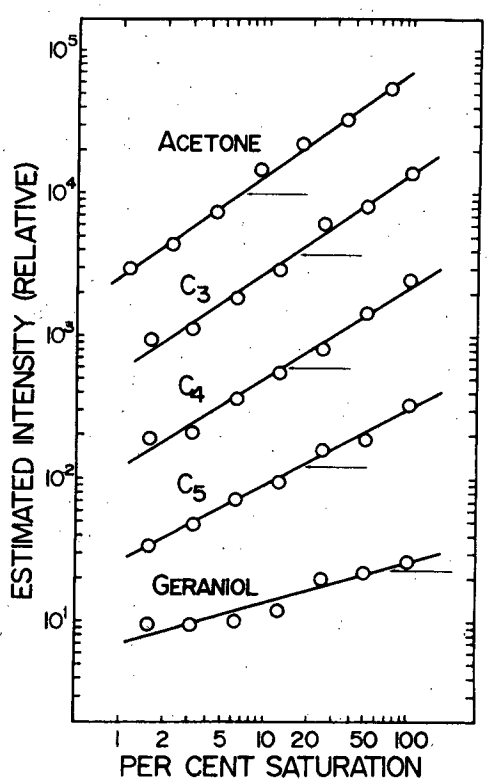


Fig. 16. Perceived intensity vs. concentration (per cent saturation in air) for acetone, 1-propanol (C_3), 1-butanol (C_4), 1-pentanol (C_5), and geraniol. The functions were displaced along the ordinate for clarity. Arrows indicate points of equal intensity across odorants and provide the means to relate the functions to each other. The functions are power functions with exponents ranging from 0.3 to 0.7. These plot as straight lines in the logarithmic coordinates of the figure. From Cain (40).

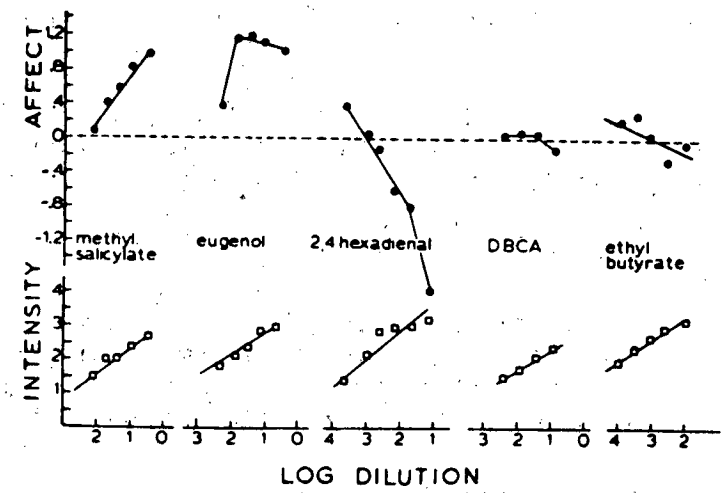


Fig. 17. Showing how both perceived intensity (logarithmic scale) and pleasantness/unpleasantness (positive and negative values respectively on linear scale) varied with dilution of five odorants. Odorant denoted DBCA is dibutylmethyl carbinol acetate. From Moskowitz, Dravnieks, & Klarman (44).

Adherence to the square root relation would suggest that a 50% reduction in ventilation rates would cause roughly 40% increase in odor intensity. Depending on the odor quality, a 40% increase in intensity may prove inconsequential or unbearable. That is, perceived intensity alone will not determine acceptability. The stimulus-response function for acceptability may follow a very different course than that for odor intensity (43). Its course may even depend on context. See Fig. 17 for how the pleasantness of various odorants changes with concentration in the rather neutral context of the laboratory (44). The relation between pleasantness and perceived intensity follows no simple rule. In the laboratory, a substance may change monotonically with concentration. This may not happen in the context of a dining room. In most real-world contexts, appealing odorants (e.g., perfumes), become more pleasant up to a certain intensity and then become less pleasant with further growth of intensity, whereas foul odorants (e.g., urine odors) become progressively less pleasant (more unpleasant) with growth of intensity. When in its proper context (e.g., the smell of a gymnasium in a gymnasium, the smell of a fish market in a fish market) an odor may vary over a moderate range of perceived intensity and still remain acceptable. The psychophysical basis for odor control should seek to specify a range of tolerable intensities for any given contaminant and should offer some insight into how rapidly acceptability will change outside this range.

Interactive Phenomena

Mixtures generally smell less intense than the sum of the intensities of their unmixed components (45). Furthermore, a complex mixture will not admit perceptual analysis into the perceived qualities of its components. This tendency for a mixture to hide both the intensity and quality of its constituents permitted creation of the art of perfumery and much of today's "art" of deodorization or reodorization (46).

Simple (e.g., binary, ternary) mixtures obey relatively simple rules. For instance, the perceived intensity (ψ_{ab}) of a mixture of two components with intensities ψ_a and ψ_b generally follows the empirically derived rule (47)

$$\psi_{ab} = (\psi_a + \psi_b + 2\,\psi_a\psi_b \cos\alpha)^{1/2}.$$

This formula for the algebraic combination of vectors has commonly yielded values of α in the range 90° to 130° for binary and even more complex mixtures (Fig. 18) (48,49). Such values imply that in certain proportions a simple (e.g., binary) mixture will smell less intense than its stronger component smelled alone. The

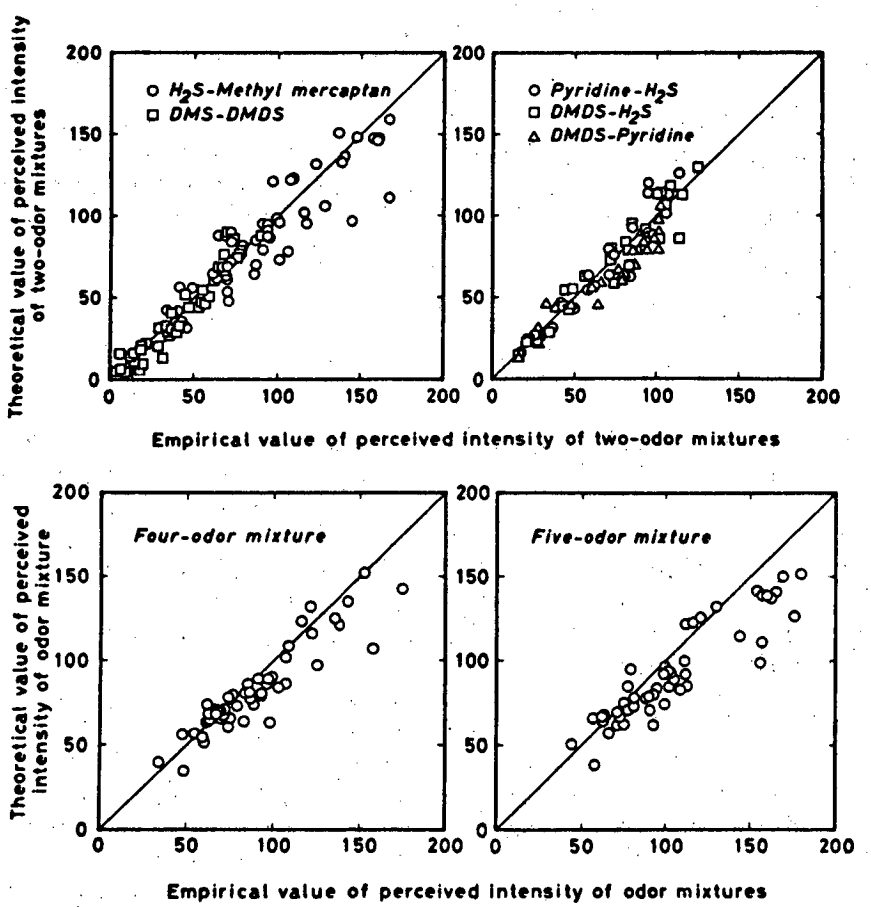


Fig. 18. Showing the relation between empirical (obtained) perceived intensity for odor mixtures of two to five components and theoretical values derived from the vector summation model. DMS denotes dimethyl sulfide and DMDS denotes dimethyl disulfide. From Berglund (48).

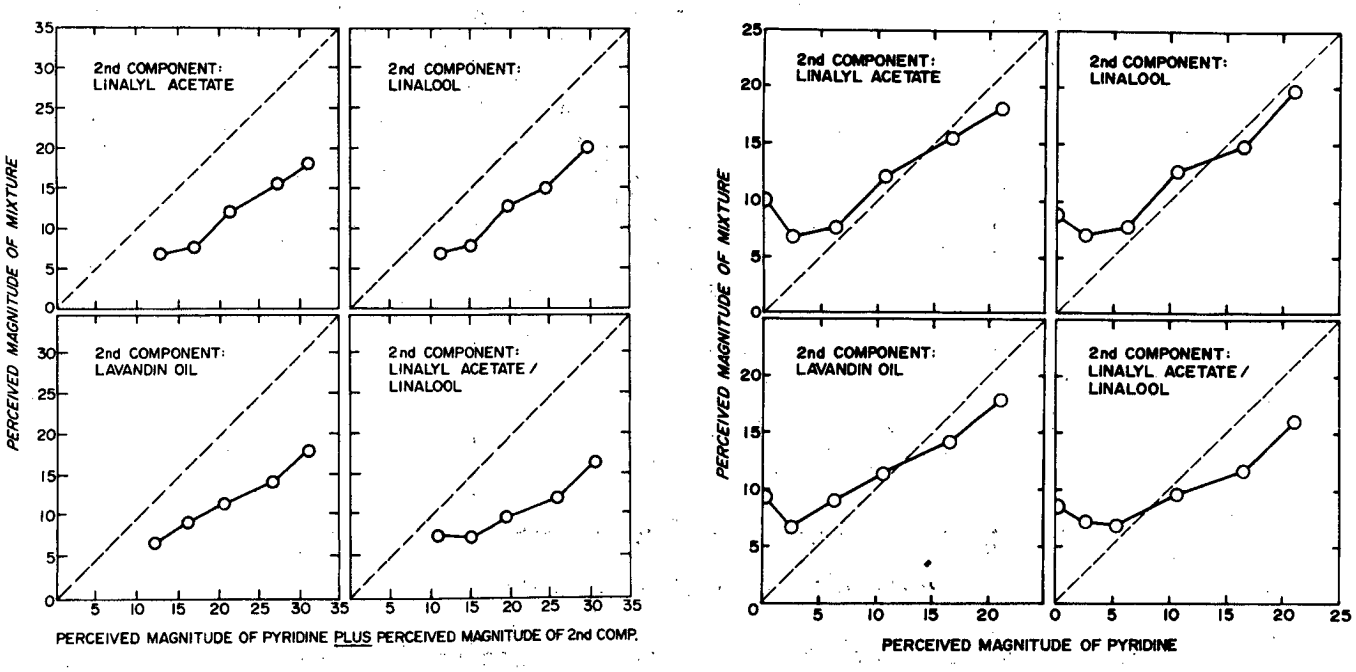


Fig. 19. Left: Perceived magnitude of mixtures containing pyridine (wide range of concentrations) and one or another second component (single concentration) vs the sum of the perceived magnitudes of pyridine smelled alone and the second component smelled alone. Right: Perceived magnitude of mixtures vs perceived magnitude of pyridine smelled alone and of second component smelled alone (Y-intercept. Nonmonotonic course of the functions and tendency of functions to fall below the dashed line give evidence of odor counteraction. From Cain & Drexler (50).

finding, empirically verified, lends some credence to the phenomenon known as odor counteraction, whereby the physical addition of a "counteractant" will yield a net decrease in odor level (50). There exists little information on whether certain substances produce more efficacious counteraction than others. Since mixtures of components chosen without respect to putative properties of counteraction have shown effects equivalent to counteraction (i.e., net reduction of intensity), the phenomenon may occur with virtually all odorants and may therefore arise generally from the way that the olfactory system responds to multiple stimulation (Fig. 19). From the small amount of data available, it seems that the olfactory system responds to dichorhinic binary "mixtures" (viz., one odorant into one nostril and the other odorant into the other nostril) in much the same way as to physical mixtures (51). Because dichorhinic mixing eliminates any interaction at the surface of the olfactory mucosa, it appears that counteraction derives from neural interaction in the central nervous system.

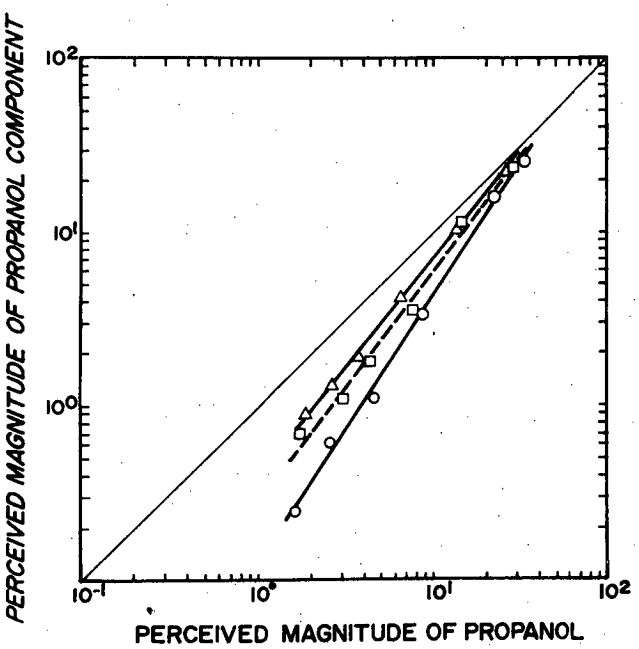


Fig. 20. Perceived magnitude of apparent propanol component in mixtures of propanol and amyl butyrate versus perceived magnitude of unmixed propanol. Tendency of points to fall below the line of identity (diagonal) reveals the inhibitory influence of the smell of amyl butyrate on propanol. Lower portion of functions reveal a strong masking influence of amyl butyrate. Circles and squares represent results obtained with physical (vapor phase) mixtures; triangles represent results obtained with dichorhinic mixtures (propanol into one nostril, amyl butyrate into the other nostril). From Cain (51).

Commercially marketed counteractants generally contain in addition to any "special" proprietary chemicals, a carefully formulated fragrance base that endows the product, at the least, with an ability to mask malodors. Most persons have learned by experience that a strong odor may "hide" a weaker odor (Fig. 20). This phenomenon, particularly evident when components are unbalanced in perceived magnitude, occurs in addition to the interactions discussed with respect to counteraction.

Masking follows subtle rules dependent on odor quality as well as on odor intensity. Malodorous qualities that may exist in unperfumed commercial products (e.g., soap) may seem mere liabilities. In the hands of a skilled perfumer, however, these qualities can be used as part of a complex mixture with an appealing fragrance. The perfumer will know, for instance, that citrus fruits contain some substances which, in isolation, smell fecal. Through suitable blending, the perfumer can mimic nature and "build" a citrus odor from pre-existing fecal notes. This forms the most sophisticated means of odor masking.

Lability

The lability of olfaction reveals itself most readily in adaptation: a time-dependent, stimulation-induced change in sensitivity. Figure 21 shows, for instance, how perceived magnitude decayed during 3-minute exposures to various concentrations

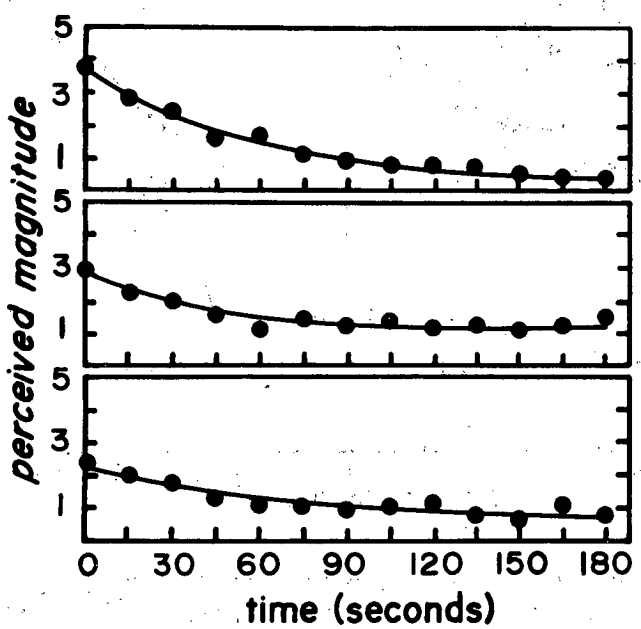


Fig. 21. Odor magnitude versus time for three concentrations of ozone: 0.3 μg/l (bottom function), 0.6 μg/l (middle function), and 1.2 μg/l (top function). From Cain (52).

of ozone (52). These functions, and those obtained with various other odorants, reveal that odor magnitude decays within minutes to a steady-state value, and sometimes to zero (53). In general, exposure to high concentrations has a more potent adapting influence than exposure to lower concentrations. A high concentration will decrease sensitivity to a larger degree and for a longer duration. In the everyday situation, persons encounter fluctuating levels of odorous contaminants (e.g., tobacco smoke, cooking odors). During the course of exposure in, say, a conference room or a restaurant the sensitivity of olfaction is modulated in accordance with both the average level of odorous contaminant and with local fluctuations in the vicinity of the observer. A person who sits next to a smoker may subsequently find the air in a distant corner odorless, whereas a visitor fresh from the outside may find that same corner unacceptably contaminanted with tobacco odor. The reduction in sensitivity that results from prior exposure restricts itself to a narrow range of stimuli. Therefore, a person exposed to tobacco smoke odor will generally find most other odorants about as detectable as usual. The ability of one substance to alter the perceived magnitude of another goes by the name cross-adaptation. Figure 22 illustrates the phenomenon (54). In the case depicted, two rather similar odorants exhibited strong cross-adaptation. Nevertheless, the degree of cross-adaptation fell well below that produced by prior exposure of each odorant to one or another concentration of itself (self-adaptation).

The process of adaptation often can cause a person to fail to notice a gradual increase in level of odorous contaminants. This situation will occur in, say, a classroom where local variations in odor are often minimal and where the level of

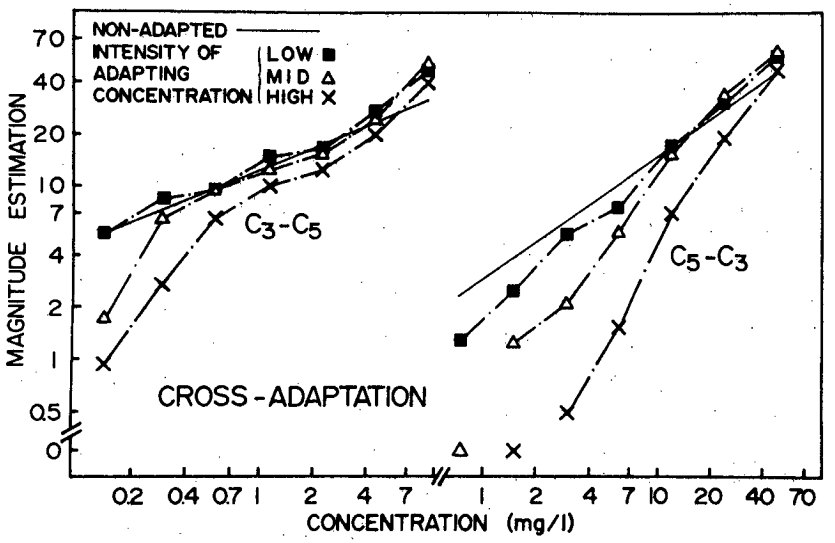


Fig. 22. Showing how previous exposure (three breaths) to 1-propanol (C_3) influenced the odor intensity of 1-pentanol (C_5) and vice versa (C_5 - C_3). Degree of cross-adaptation shown between these chemically similar substances is asymmetrical and considerably less than that obtained with self-adaptation (C_3 - C_3, C_5 - C_5). Less similar substances often show only trivial or no cross-adaptation. From Cain (54).

odorous effluent from bodies increases with time of occupancy. As Winslow stated with respect to odors of occupancy (12): "The organic substances present, manifest as body odors, may exert a depressing effect upon inclination to work and upon appetite; therefore, occupied rooms should be free from odors which are obvious to anyone entering from without. (Such odors are never perceived by those who have been continuously in the room while they have been accumulating.)" [p. 77-78]

Another time-dependent phenomenon, termed habituation, may lead to acceptance of a foul smelling odorant even without any apparent change in sensitivity. Persons who work in foul-smelling industries will find that an initially offensive atmosphere loses its ability to annoy in time. Even upon entering the atmosphere after many hours off the job, the worker may find the once-offensive atmosphere quite tolerable though no less intense. The phenomenon of affective habituation has revealed itself readily in the laboratory (55).

Common Chemical Sense

The epithelium of nasal cavity contains free nerve endings of the trigeminal nerve, which endows the mucosal tissue of the head (lips, nose, mouth) with chemical sensitivity. An inhaled gas will often stimulate these nerve endings at the same time that it stimulates olfactory receptors. Indeed few substances display any categorical ability to stimulate either olfaction alone or the trigeminal nerve alone (56). Generally, however, substances will stimulate olfaction at concentrations much lower than needed to stimulate the trigeminal nerve. Stimulation of

this nerve reveals itself through the perceptual attributes of pungency, irritation, pain, coolness, or warmth (57). These comprise the attributes of the common chemical sense, a term used to describe the modality that subserves this constellation of attributes in mucosae at various body loci.

Particularly effective stimuli for the trigeminal nerve include highly reactive organic and inorganic substances such as strong acids and bases, substances with unsaturated carbon linkages, halogenated substances (1). Even these may still stimulate olfaction at concentrations slightly below those necessary to stimulate the common chemical sense. Less reactive substances will stimulate olfaction generally at orders of magnitude lower in concentration than necessary to stimulate the common chemical sense. Many of the stronger irritants possess dangerous, corrosive properties. An inspection of the justification for Threshold Limit Values (TLVs) reveals that sensory irritation forms the basis to control the concentration of many substances in the workplace (58).

The perceived magnitude of irritation grows relatively rapidly with concentration. Fig. 23 shows that the magnitude of the integrated response of the trigeminal nerve grows disproportionately with concentration (59). The functions shown here conform to power functions with exponents greater than 1.0. Responses from olfactory structures yield exponents below 1.0 (60).

Figure 24 also reveals the rapid growth of the trigeminal response (in this case perceived irritation) by comparison to the olfactory response (perceived odor magnitude) (61). The psychophysical method (category estimation) used to obtain these functions favored the use of a logarithmic curve to describe the results. The substantive point regarding the rapid growth of the trigeminal response remains unaltered by this technicality.

Various malodors, including tobacco smoke, evoke common chemical sensations. These sensations may persist after odor has faded and may possibly give rise to the discomfort expressed by occupants who may claim to notice no odor after a while in a poorly ventilated place (62). Indeed, Yaglou, Coggins, and Riley found that occupants exposed to "occupancy odor" from themselves and others would eventually fail to notice the odor but could still assess air quality accurately (17). Fig. 25 shows the relation between the odor estimates of visiting judges and the air quality estimates of the occupants. The curvilinear relation presents circumstantial evidence that a slowly adapting "high threshold" sensory system, such as the common chemical system, provided the information to judge air quality. Whereas odor diminishes in perceived magnitude with time, irritation follows a more complicated course. It may increase or even oscillate (63, 64).

Physical Factors in Odor Perception and Ventilation

Ventilation serves to eliminate contaminants by means of dilution. In some cases the furnishings in an enclosed space may also serve to eliminate contaminants. Odorous materials may adsorb to walls, curtains, etc. Such materials may mute the impact of episodic odor pollution (e.g., precipitous generation of odors from cooking), but may subsequently act as secondary sources. Odorants adsorbed at one time may desorb at a later time. The rate of desorption will often depend on physical factors, particularly temperature and humidity. Interestingly, the olfactory system itself also seems depend on these physical factors.

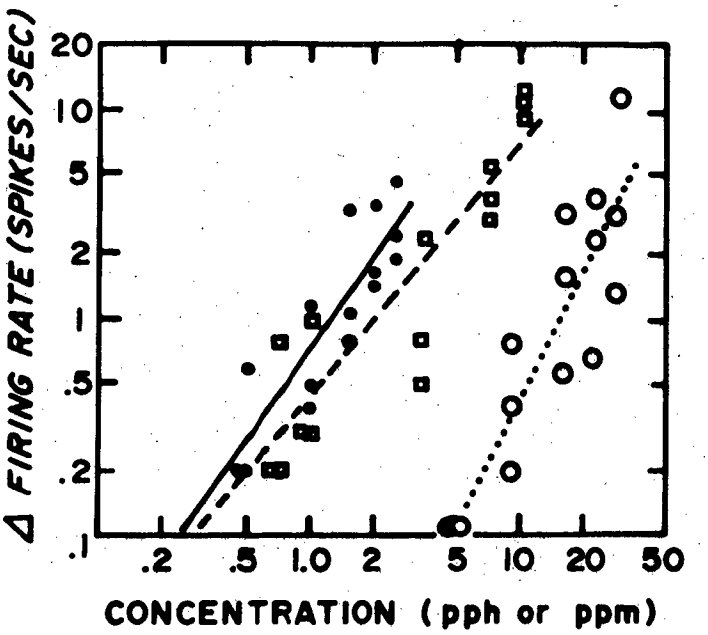


Fig. 23. Response of nasopalatine branch of the trigeminal nerve in the rat to concentrations of formaldehyde (filled circles, ppm scale), amyl alcohol (squares, pph scale), and ozone (open circles, ppm scale). Adapted from Kulle and Cooper (59).

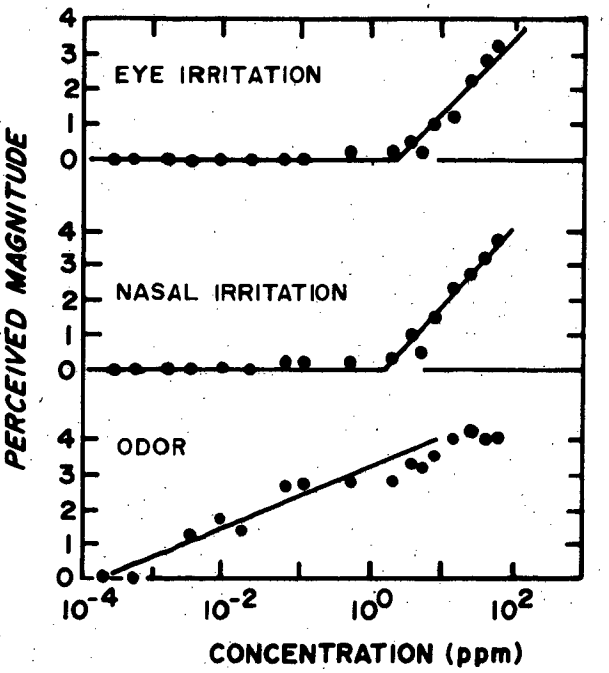


Fig. 24. Showing how eye irritation, nasal irritation (pungency), and odor intensity varied with the concentration of benzyl mercaptan. Adapted from Katz & Talbert (61).

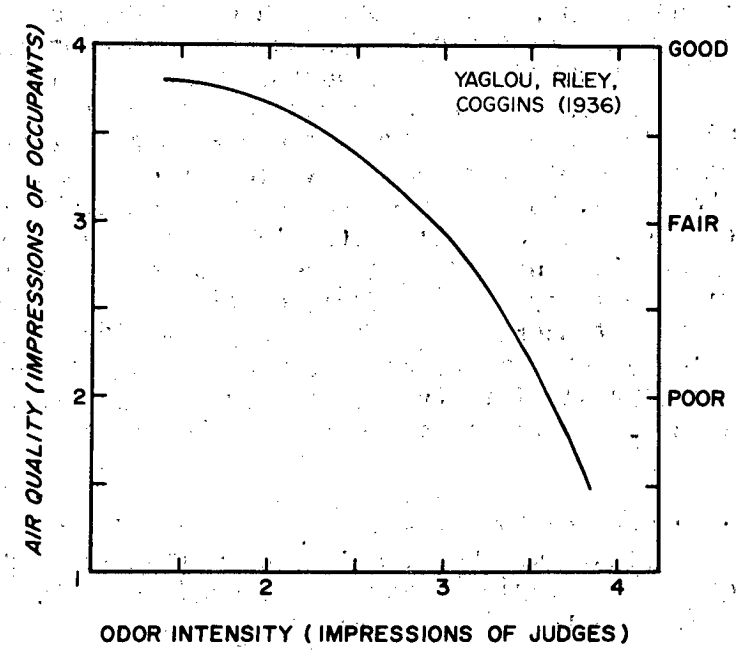


Fig. 25. Showing how judgments of air quality obtained from persons who had occupied a chamber for up to 3.5 hrs varied with judgments of odor intensity obtained from observers who entered the chamber briefly. Adapted from Yaglou, Riley, & Coggins (17).

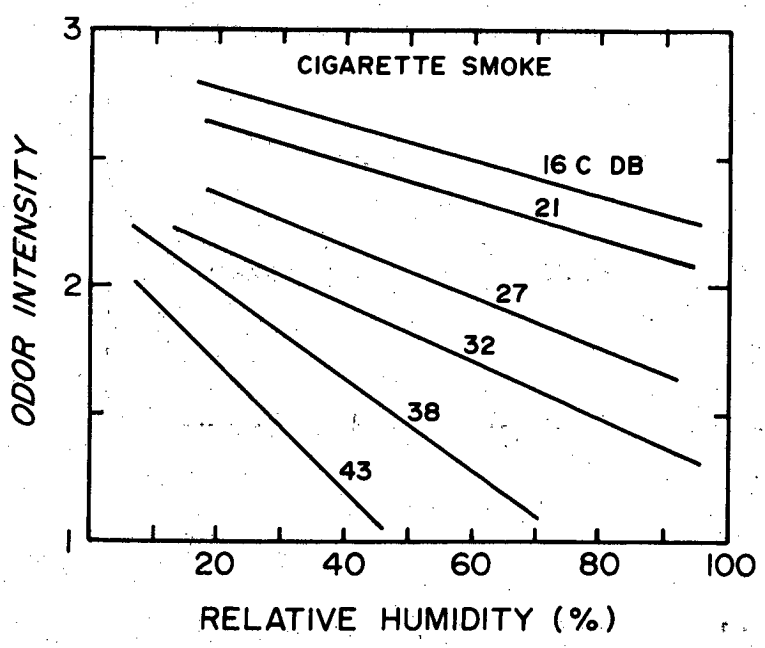


Fig. 26. Showing how odor intensity of cigarette smoke varied with relative humidity at various dry-bulb temperatures. Adapted from Kerka & Humphreys (67).

The N. Y. State Commission on Ventilation decided that high humidity exacerbated body odor in classrooms (10). This observation could have derived from the accumulation of potentially odorous perspiration on skin and clothes. Bacterial action makes unevaporated perspiration become odorous. Kuehner also noted that various materials, e.g., linoleum, generate odorous contaminants at a higher rate under high humidity (65). This may not prove a general rule. It seems highly unlikely that all potentially odorous materials would exhibit humidity-dependent evaporation. On the other hand, both Kuehner and Kerka and Humphreys concluded that, as a general rule, the sense of smell actually becomes less sensitive under high humidity (66). Figure 26 illustrates how the perceived intensity of tobacco smoke varied with relative humidity. The decreasing lines depict humidity-dependent changes for constant dry bulb temperatures. The figure implies that perceived odor diminishes with both humidity and temperature. Grundvig, Dustman, and Beck also found a reduction in olfactory sensitivity with dry-bulb temperature (see Fig. 27) (67). Some other investigators have failed to find either of these changes (68, 69).

Kerka and Humphreys uncovered humidity and temperature dependence for the perceived odor magnitude of various pure substances, including isovaleric acid, methyl salicylate, and pyridine. These various results led Woods to suggest a relation between odor and enthalpy, a matter illustrated in Fig. 28 (70).

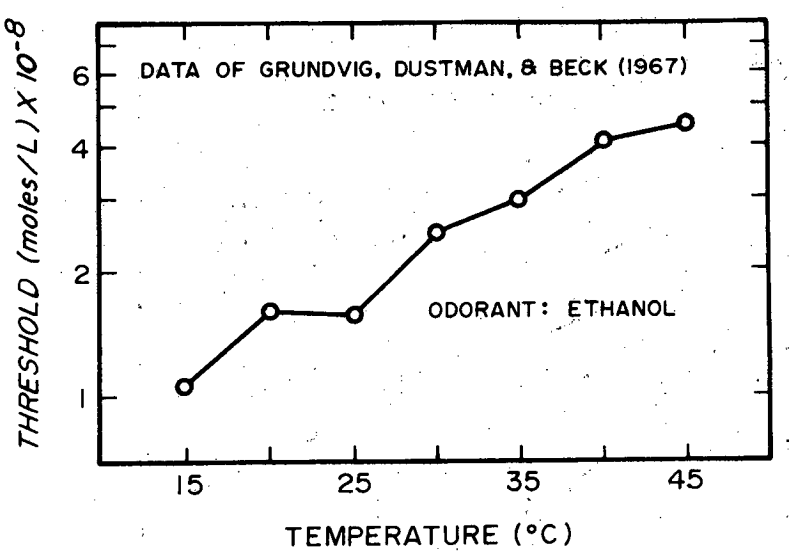


Fig. 27. Showing how the threshold concentration for ethanol varied with dry-bulb temperature.

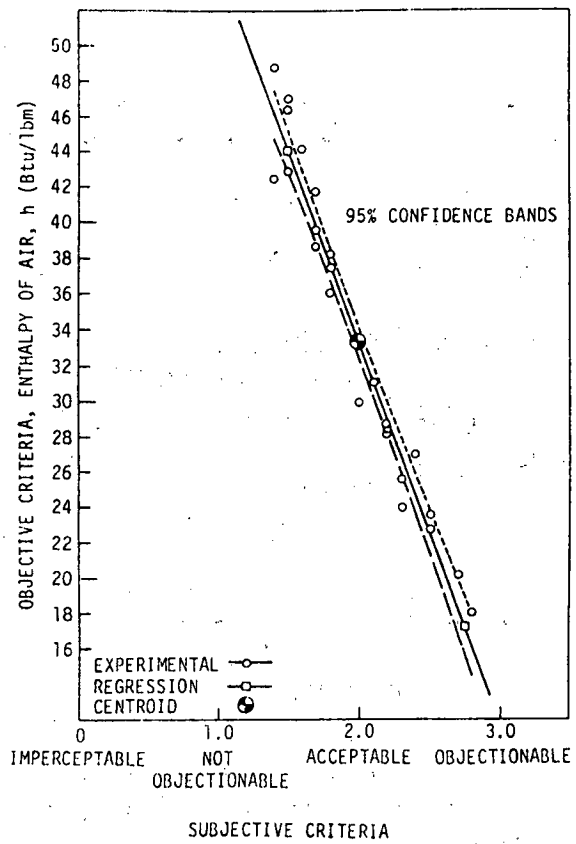


Fig. 28. Showing the relation between air enthalpy and odor intensity of cigarette smoke. Data from Kerka and Humphreys as analyzed and presented by Woods (70).

The apparent dependence of odor magnitude on humidity and temperature led Cain (71) to consider whether an increase in indoor humidity would offer an energy-efficient means to counterbalance a reduction in ventilation rates. Kerka and Humphreys' data, gathered in an experimental chamber, implied that an increase in humidity from, say, 20% to 55% RH at a dry bulb temperature of 21 C could counterbalance a 30% reduction in ventilation rates. These particular numbers could represent, for example, the reduction in ventilation rates (30%)recommended by ASHRAE Standard 90-75, Energy Conservation in New Building Design compared to previous recommendations, ASHRAE Standard 62-73, Standards for Natural and Mechanical Ventilation. The increase in humidity (20 to 50% RH) could represent that achievable in an office (21 C) in Minneapolis where average outdoor temperature in winter equal -2.2 C with a humidity ratio of 0.0031. Unfortunately, calculations indicated that the energy needed for humidification would just about cancel any energy savings achieved through the 30% reduction in ventilation.

Changes in temperature and humidity even within the thermal comfort zone can apparently influence odor perception to a degree equivalent to a fivefold change in rate of generation of odorant. Nevertheless, olfaction seems least sensitive at high temperatures and humidities, where rate of generation might be highest. It would seem wise to measure just how rate of generation varies with these factors.

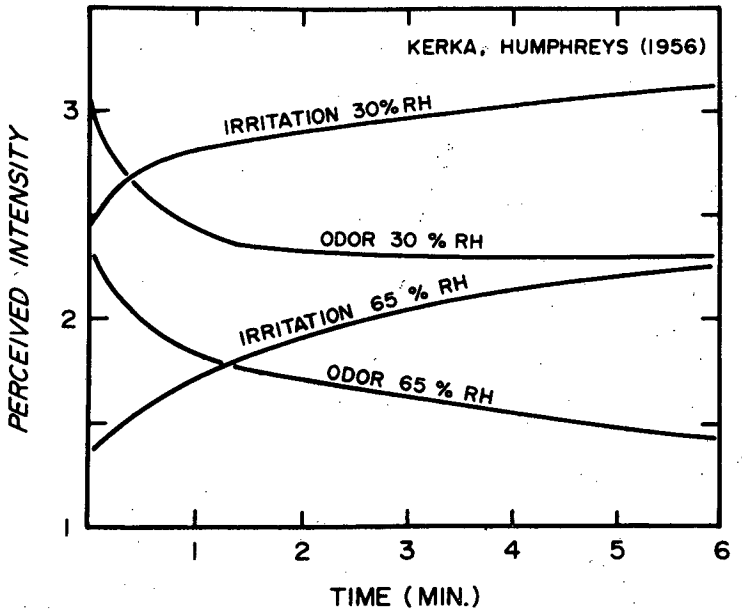


Fig. 29. Showing changes in odor and irritation during continuous, short-term exposure to cigarette smoke generated in a chamber. Air supply to the chamber equalled 70 cfm (35 L/s) and ventilation equalled 14 cfm/cigarette (7 L/s · cigarette). Dry bulb temperature equalled 25 C. Adapted from Kerka & Humphreys (66).

Most experiments on humidity dependence of olfaction have concerned themselves with very brief exposures to odorant. Kerka and Humphreys gave some slight attention to longer exposures and obtained the rather striking results shown in Fig. 29. The figure shows how the odor of cigarette smoke diminished over time and how irritation from the smoke increased over time. Both of these attributes showed marked humidity dependence, a dependence magnified by time.

Humidity may also play a role in the use of granular media to remove odorants. Although a medium such as charcoal allows water vapor to pass, it hinders the passage enough to allow the vapor to interact with other substances adsorbed on the medium. This may lead to conversion of some adsorbed products. If and when such products pass through the medium they may give rise to odors not present before introduction of filter medium.

Odor Perception and Health: Some considerations

As noted in the first part of this report, persons often perceive a connection between odors and health. Indeed, until the end of the 19th century medical practice in most parts of the world contained the implicit or explicit notions that certain foul smelling (viz., putrid) substances caused disease, certain acrid smelling substances cured disease, and various pleasant smelling substances (e.g., rue, pennyroyal, jasmine) offered personal protection against infection. Hence, an apparent connection

between odors and health has deep roots. It also has shallow experimental verification. The conclusion of the New York State Commission in 1923 that odor can depress appetite arose again in the following decade, when Winslow and Herrington (72) reported that heated dust odor, like occupancy odor, can diminish the appeal of food. Such a finding contains relatively little information; virtually everyone recognizes a connection between odors and appetite simply through personal experience. The Commission's companion finding that occupancy odor diminishes the inclination to work seemed more surprising, but seems also contradicted by the observation that workers in malodorous industries eventually seem completely uninfluenced by the odor.

The reported adverse human reactions to odors range from strictly local effects, such as reflex engorgement of the nasal epithelium, to global and systemic effects, such as a combination of headache, dizziness, and nausea (73). Reflex changes arise generally from substances that stimulate the trigeminal (i.e., common chemical) system. This may occur indoors most notably from formaldehyde, cigarette smoke, and oxidants. Though not understood thoroughly, the mechanism for such reflex changes seems understandable in principle and presumably has little to do with the actual perception of the airborne agents. Such theoretical certainty fades somewhat with respect to reported allergic reactions to odors. Allergists often report cases of bronchoconstriction specifically to odorous materials, but offer little resolution regarding whether the bronchospasm results from the direct action of the airborne substance on lung tissue or from a "conditioned" response to odor.

Reactions such as dizziness, headaches, and nausea seem to occur most often to unpleasant industrial emissions. In general, the offended population grows more sensitive with duration of exposure (weeks, months, years). In this respect, the reaction apparently diverges from that of the industrial worker, who reportedly becomes apathetic with time. These divergent reactions could stem from different ascriptions of meaning. The resident near an odorous factory may see the emission as a sign of unhealthful conditions, a threat to well-being, an embarrassing intrusion. Adverse somatic reactions may appear merely to follow such an ascription. This conclusion, no matter how tempting, seems too facile. It invites disinterest in a phenomenon too widespread to be ignored. It fails on the surface to recognize that the industrial worker is generally self-selected and that even some such workers may fail to habituate to the ill effects of malodors. (Workers in an office, self-selected by a criterion different from that of a production-line worker, would probably fail to tolerate most industrial odors if these were to appear in the office.) Furthermore, the facile conclusion may inhibit exploration into such whether some identifiable groups of persons may exhibit particular sensitivity to certain airborne substances and may have an amplified reaction if odor accompanies inhalation of the substance. Hence, the fabric of adverse reactions to odors requires considerably more study. It seems noteworthy, however, that virtually all studies of ventilation requirements imply that visitors to a space will generally encounter some odors. The issue of possible adverse reactions to indoor odors therefore concerns perceived intensity, perceived character, and chemical composition of contaminants rather whether or not odors in general will be tolerated.

ANALYTICAL AND PSYCHOPHYSICAL MEASUREMENT

A thorough characterization of the atmospheric environment indoors requires both analytical and psychophysical measurement. Analytical techniques, such as the collection of gas samples and the chemical characterization of the samples via gas-chromatography and mass spectrometry, derive from a now well-developed technology (74). It is noteworthy that investigations of ventilation requirements generally preceded the development of this technology. Hence, possible correlations between concentration of commonly occurring indoor contaminants and odor level remain largely unstudied.

In the occupational environment, analytical techniques alone may suffice to decide ventilation rates. This occurs because many industrial processes allow the ventilating engineer to anticipate the composition of contaminants. Outside the occupational environment, however, there exists no straight-forward way to anticipate composition (75). Since ventilation generally serves in these cases to produce an esthetically pleasing environment, sensory measurement must necessarily play a role. A correlation between psychophysical and analytical data, if achievable, offers the greatest leverage for the control of odor relevant contaminants (76).

Because psychophysics must play a predominant role in the determination of ventilation requirements, the character of research on ventilation requirements for commercial, residential, and institutional spaces will share much in common with earlier research. Techniques of psychophysics have evolved progressively (73). The following section highlights some methods applicable to research on ventilation.

Psychophysical properties of interest in the characterization of an odorous contaminant include detectability (threshold), psychophysical function (perceived magnitude versus concentration), preference-aversion function (perceived pleasantness/unpleasantness versus concentration), and odor character (perceived quality).

Standard techniques of sensory measurement, carefully applied, offer straightforward means to measure both detectability and the psychophysical function. As in the exploration of other sense modalities, the choice of suitable techniques will depend on the time available for measurement and on the desired precision of the outcome. For instance, the measurement of detectability should enable subjects to compare samples that contain a stimulus (in this case, odorant) with samples that do not (unodorized air) (77). When time presents no obstacle, a subject could judge each of many concentrations (and accompanying blanks) several hundred times. Such a procedure, achievable in auditory research, where automatic presentation of stimuli and relative absence of adaptation permit more than a score of judgments per minute, is incompatible with olfactory research, where a subject must voluntarily inhale the stimulus and where loss of sensitivity via adaptation occurs rapidly. The number of trials achievable in olfaction equals about 1 to 2 per minute, only 5 to 10% of the rate achievable in audition. This limitation has led to adoption of techniques such as the following (78). A subject smells a sample of weakly odorized air along with two blanks and must choose one or another sample (forced-choice method). For the next triad, the sample of odorized air is three times more concentrated than that smelled previously. As before,two blanks accompany the odorized sample. A progression from weaker to stronger concentrations continues until the subject chooses correctly on three successive occasions, whereupon the ascending progression ends. After a brief respite, the subject may

begin again at the weakest (i.e., most dilute) level and may then advance upward again. In field testing, however, one ascending run per subject may need to suffice and an average point of detection computed across 8 to 10 subjects (79).

The ascending forced-choice procedure admits to minor variation in number of blanks, size of the concentration step, string of correct responses necessary to cease testing, etc., but incorporates two essential features: 1) it removes certain response biases inherent in techniques that may require responses of merely yes or no, and 2) it minimizes the problem of adaptation inherent in the presentation of weak stimuli after strong. An olfactometer developed at IIT Research Institute was designed with the requirements of the ascending forced-choice technique (three alternatives per trial; threefold change in concentration from step to step). This device, when set to deliver odorous air at 3 L/min, yields measures of detectability close to those obtained when subjects smell odorant in the ecologically valid situation (still air in a room).

Like the measurement of detectability, the measurement of supraliminal odor magnitude rests on principles relevant to all sensory measurement. The prototypical operation in sensory measurement involves intrasensory matching wherein a person chooses or adjusts some reference stimulus to match some test stimulus in one or another attribute (80). Much of visual psychophysics rests on binocular brightness matching, e.g., matching the brightness of a target presented to the left eye to the brightness of a target presented to the right eye. Similarly, much of

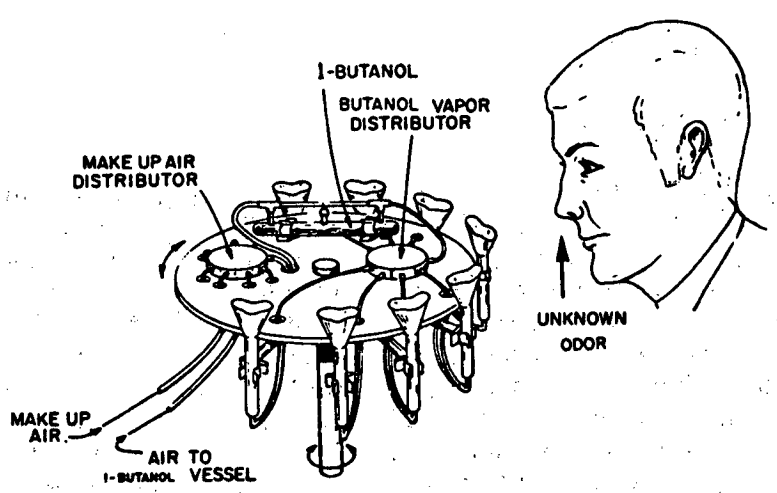


Fig. 30. Showing a subject using the butanol olfactometer (lazy Susan configuration) to find an odor intensity that matches an unknown stimulus. As customarily arranged, the device delivers concentrations ranging from 16 to 2000 ppm. From one port to another, concentration changes by a factor of 2.0. From Dravnieks (83).

auditory psychophysics rests on binaural loudness balances. In vision and audition, virtually every conceivable matching operation has seen some use. In audition, the most widely used matching procedure involves the use of a 1,000 Hz tone and has led to the construction of the well known phon scale. This designates the loudness of a test sound in terms of the sound pressure level (in dB) of a matching tone of 1,000 Hz (81).

A butanol reference scale provides an olfactory analogue of the phon scale (82). Fig. 30 shows a subject using a device that has come to be known as the butanol olfactometer (83). It delivers concentrations ranging from weak to strong and a subject seeks to choose the one port out of eight that matches any given test stimulus. If the test stimulus seems of a magnitude that falls between adjacent ports, then the subject may so indicate. Lindvall and Svensson have devised a similar scheme to match unpleasantness (84). In this case, subjects choose a concentration of the unpleasant smelling substance hydrogen sulfide to match the unpleasantness of a test stimulus. This technique of unpleasantness matching has seen much less use than the procedure of intensity matching with butanol. Judgments of pleasantness and unpleasantness are commonly made instead by graphic rating (line marking) techniques (44, 55).

The phon scale has a useful and important companion known as the sone scale. The sone scale arises from direct numerical estimates of loudness (L) and follows the equation $L = kP^{0.6}$ where P is sound pressure and k is a proportionality constant (85). Whereas the phon scale merely permits specification of a test stimulus in terms of some sensory equivalent, the sone scale permits specification in terms of actual perceived loudness derived from direct estimation. Moskowitz, Dravnieks, Cain, and Turk followed the "auditory model" in a recommendation that the perceived intensity of butanol, possibly in conjunction with butanol matching as discussed above, could serve the same purpose in olfaction that the sone scale serves in audition (86). As it turns out, the relation between the odor intensity (R) of butanol and concentration conforms to an equation that bears striking similarity to that for the sone scale:

$$R = kC^{0.66}$$

where C is concentration (see Figs. 31 & 32).

It is noteworthy that techniques known as ratio-scaling procedures have generally supplanted category scaling techniques of the sort used by Houghten, Yaglou, Lehmberg, and others (88). The commonly-used ratio scaling technique of magnitude estimation requires subjects to assign numbers proportional to sensory magnitude. Hence, a value of 4 on such a magnitude scale would represent twice a value of 2 and a value of 30 would represent three times a value of 10, and so on. Such relations do not hold true for the annotated category scale shown in Table 5. Among other virtues, ratio scales place no arbitrary limitations on the resolution of small differences. Furthermore, the scales place no limitations on the use of psychophysical data to erect quantitative models of how to achieve an acceptable odor environment in a most energy-efficient fashion.

Category scaling procedures possess the asset of simplicity. Unlike ratio scaling procedures, which offer the subject no anchored endpoint (e.g., "overpowering" odor on Yaglou's scale) or annotations (e.g., "weak," "moderate"), category scaling techniques pose no apparent threat to the judgmental capabilities of children or to the most casual subject. For this reason, category scaling sees primary use in the field and ratio scaling in the laboratory.

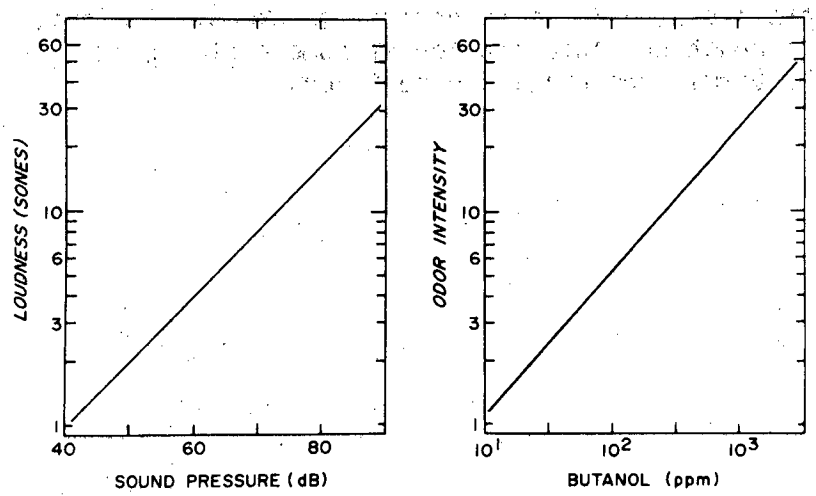


Fig. 31. Left: Psychophysical function for loudness of a 1,000 Hz tone. This function, known as the sone function, is used to convert into a measure of loudness the level of the 1,000 Hz tone matched to any given test stimulus. Right: Psychophysical function for the odor intensity of butanol. This function is the olfactory analogue of the sone function.

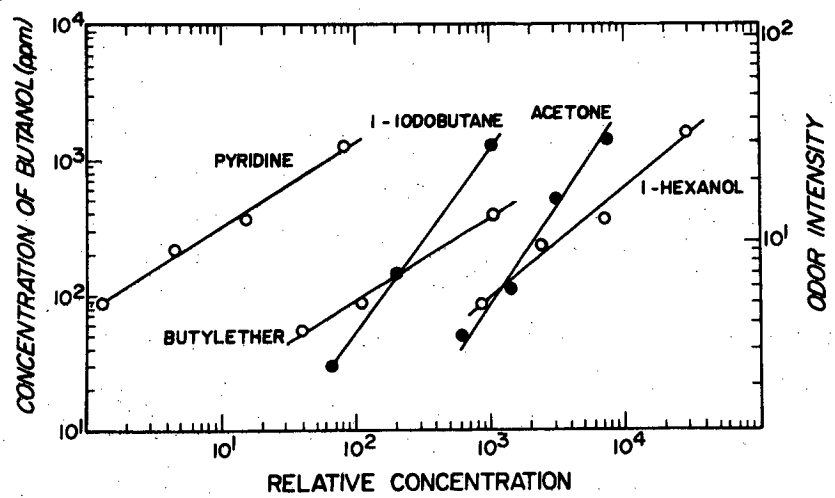


Fig. 32. Psychophysical functions for various odorants. The functions were obtained by matching butanol (see left ordinate) to the various concentrations of each odorant. Right ordinate shows odor intensity derived via the psychophysical function for butanol. Data from Dravnieks & Laffort (87).

Because of its inherent multidimensionality, odor quality lends itself to quantitative characterization only by means of cumbersome techniques. These include the use of standard descriptors (profiling technique) or direct estimates of similarity followed by multidimensional scaling (89, 90). The profiling technique may employ more than 100 potential descriptors. Irrespective of whether the descriptors are used for a composite measure of similarity they can at least provide a rough characterization of some contaminant of uncertain origin and may thereby permit the origin to be traced.

SUMMARY AND PROSPECTS

The report has shown that odor control has long played a governing role in ventilation. In the 19th century, concern with odors derived primarily from concern with health, specifically with fear of human emanations known as anthropotoxin, etc. More recently, concern with odors has derived from esthetics. In the olfactory realm, apparent healthfulness and esthetics form correlated continua. Odor preferences undoubtedly originate from judgments regarding the apparent healthfulness, safety, and other beneficial or harmful attributes of odorous materials.

When ventilation occurs via natural means (e.g., through windows) thermal factors, rather than chemical factors, actually seem to govern the need for fresh air supply. The amount of fresh air necessary to maintain comfortably cool conditions will usually maintain acceptably odorless conditions. When ventilation is delivered via mechanical means, it becomes possible to control temperature independently of the chemical quality of the indoor air. Under these circumstances, the need for odor control will generally govern the need for fresh air supply.

Outright acknowledgement and understanding of the role of odors in ventilation emerged in the 1930s when Yaglou and colleagues at Harvard School of Public Health performed laboratory experiments on the amount of fresh air necessary to dilute body (occupancy) odor to an acceptable level. The experiments established the dual principles that ventilation should be determined per occupant (i.e., use of the occupant as the unit of demand) and that the rate per occupant should increase progressively with density of occupancy. The reason for the second principle remains obscure. Yaglou ascribed it to the instability of body odor and to a reduction in the efficiency of air clearance under conditions of crowding. This matter deserves additional attention. Indeed, a re-examination of the ventilation requirements for body odor has justification on various grounds: 1) modern standards of personal hygiene may have altered the need for ventilation, 2) field studies, with occupants in their normal context, should supplement any laboratory investigations, 3) tracer gases can verify actual ventilation rates in the laboratory and in the field, 4) techniques of psychophysical measurement now obviate the need for the cryptic, annotated rating-scales used in early research, 5) gas chromatography and mass spectrometry can offer guidance regarding odor-relevant contaminants in indoor air, and 6) analytical instruments can assess the stability of contaminants over time.

After a brief flurry in the 1930s, research on ventilation requirements almost ceased. Hence, many relevant questions received little attention or none whatsoever. Those of particular interest in the present context include type of odor (occupancy, tobacco, etc.), occupation density, differences in impressions between occupants adapted to prevailing conditions and visitors, influence of temperature and humidity on both the generation and reception of common contaminants, and the efficacy of gas filtration. These variables are now receiving attention in laboratory experiments in a new aluminum-lined environmental chamber (John B. Pierce Foundation Laboratory) and in field studies in schools, hospitals, and offices (TRC of New England). These investigations combine modern methods of olfactometry and psychophysics (e.g., odor matching via the butanol olfactometer, measurement of odor detectability via a forced-choice triangle olfactometer) with modern techniques of analytical chemistry (e.g., collection of organic vapors on adsorbent polymers and subsequent GC/MS analysis). The laboratory experiments will also

include particulate monitoring in order to explore such matters as whether changes in the concentration and size distribution of particulates correlates with changes in the intensity and character of tobacco smoke odor over time.

Quantitative estimates of ventilation requirements for, say, tobacco smoke odor under various environmental conditions, various densities of occupation, etc. take on particular importance in a context of energy conservation. ASHRAE Standard 62-73 sets 5 cfm (2.5 L/s) per occupant as an absolute minimum for any occupied space. This low value represents the rate theoretically necessary to insure adequate control over the concentration of carbon dioxide. (Some persons argue that even lower rates would provide satisfactory control.) This generally-occurring, odorless contaminant receives special consideration because, unlike most other contaminants, it resists removal by means other than ventilation. Control of odorous contaminants invariably requires greater rates of ventilation, but yet such contaminants lend themselves readily to removal by means such as filtration. It can therefore be argued that ventilation rates greater than 5 cfm (2.5 L/s) per person waste some portion, often sizeable, of the energy necessary to condition ventilation air. For this reason, the performance of odor removing means (e.g., activated carbon filters) requires attention both in present and future research.

Building designers and HVAC engineers have shown little proclivity to employ filter media, such as activated carbon, for energy conservation. The reasons for this reluctance seem to originate from three sources:

1) Some engineers voice the feeling that most buildings are so highly over-ventilated, by means of both deliberate air intake and adventitious infiltration, that moderate-to-large nominal reductions in ventilation will have little impact on the concentration of indoor contaminants. Engineers often report that closing air intakes leads to no discernible increase in complaints.

2) Local codes do not encourage or permit large reductions in ventilation. Even in jurisdictions with energy conservation codes, a requirement to exhaust relatively large amounts of air from lavatories may thwart strict adherence to the low ventilation rates recommended by the codes. From a practical standpoint, this situation presents the same difficulty (i.e., large amounts of infiltration) as that voiced in point 1 above.

3) The use of filter media presents a variety of technical and economic uncertainties. The technical uncertainties are highlighted in the following statement, made with respect to granules of activated alumina impregnated with potassium permanganate (marketed as Purafil) but generalizable to other media (30):

> In the use of the above performance data the designer must be reminded that each space constitutes a different odor problem. Total odor load, rate of generation and required end result are all variables. It is evident that the slower the air moves and the more pellets it has to pass through, the higher will be the deodorant efficiency. Also, the more pellets in a given filter bed the longer will be the interval before these must be replaced. On the other hand, the deeper the bed the higher will be the pressure drop penalty placed on the air handling system. Accordingly, the chosen configuration of the filter will be a compromise between the optimum efficiency per pass, an acceptable life, and a permissible static pressure. [p. 673]

Such comments reflect the need for careful planning in the installation and maintenance of filters. The matters of air velocity at the face of the filter and pressure drop across the filter (a function of particle diameter and filter thickness) will determine single-pass efficiency and power consumption for filtering. Some such characteristics can be obtained readily or calculated. Unfortunately, however, there exists little standardization in the means to compare the efficiency of filters challenged with common mixtures of contaminants. Other matters that deserve attention in a research setting include 1) the best method to signal the saturation of granular media, 2) estimation of the life of a granular filter, 3) the sensory and objective qualities of filtered air, and 4) examination of alternative media or combinations of media.

The technical complications that may inhibit the installation of filters will presumably be eliminated by appropriate research. Most likely, filtration will serve as only one means to deal with indoor contaminants. Variable (intermittent) ventilation will undoubtedly serve as another way. Furthermore, current research may reveal that lower rates of ventilation than those specified previously will cause no deterioration of indoor air quality. Irrespective of which route proves most fruitful, research on ventilation and related matters must strive toward control over the indoor atmosphere. Only control will lead to the dual goals of a healthful indoor environment and energy efficiency.

REFERENCES

1. R. W. Moncrieff, The Chemical Senses (Leonard Hill, London, 1967), 3rd ed.

2. J. H. Cassedy, Charles V. Chapin and the Public Health Movement (Harvard University Press, Cambridge, MA, 1962).

3. F. A. R. Russell, "The Atmosphere in Relation to Human Life and Health," Smithsonian Miscellaneous Collection, Publication No. 1072 (1896).

4. I. Andersen, "Formaldehyde in the Indoor Environment-Health Implications and the Setting of Standards," in P. O. Fanger and O. Valbjørn, Eds., Indoor Climate (Danish Building Research Institute, Copenhagen, 1979), pp. 65-87.

5. G. R. Lundqvist, "The Effect of Smoking on Ventilation Requirements," in P. O. Fanger and O. Valbjørn, Eds., Indoor Climate (Danish Building Research Institute, Copenhagen, 1979), pp. 275-292.

6. C. D. Hollowell, J. V. Berk, and G. W. Traynor, "Impact of Reduced Infiltration and Ventilation on Indoor Air Quality," ASHRAE Journal, 21(7), 49 (1979).

7. A. Dravnieks, "Measurement of Odours in an Indoor Environment," in P. O. Fanger and O. Valbjørn, Eds., Indoor Climate (Danish Building Research Institute, Copenhagen, 1979), pp. 127-139.

8. L. Paul, "Die Wirkungen der Luft bewohnter Räume," Zeitschrift für Hygiene 49, 405 (1905).

9. L. Hill, M. Flack, J. McIntosh, R. A. Rowlands, and H. B. Walker, "The Influence of the Atmosphere on our Health and Comfort in Confined and Crowded Places," Smithsonian Miscellaneous Collection, Publication No. 2170 (1913).

10. New York State Commission on Ventilation, Ventilation (Dutton, New York, 1923).

11. A. K. Klauss, R. H. Tull, L. M. Roots, and J. R. Pfafflin, "History of the Changing Concepts in Ventilation Requirements," ASHRAE Journal 12(6), 52 (1970).

12. C.-E. A. Winslow, Fresh Air and Ventilation (Dutton, New York, 1926).

13. F. C. Houghten, H. H. Trimble, C. Gutberlet, and M. F. Lichtenfels, "Classroom Odors with Reduced Outside Air Supply," ASHVE Transactions 41, 253 (1935).

14. W. S. Cain, "Ventilation and Odor Control: Prospects for Energy Savings," ASHRAE Transactions, 85(1), 784 (1979).

15. W. H. Lehmberg, A. D. Brandt, and K. Morse, "A Laboratory Study of Minimum Ventilation Requirements: Ventilation Box Experiments," ASHVE Transactions 41,157 (1935).

16. C.-E. A. Winslow, Comment on "A Laboratory Study of Minimum Ventilation Requirements: Ventilation Box Experiments," p. 165 (see 10 for complete reference).

17. C. P. Yaglou, E. C. Riley, and D. I. Coggins, "Ventilation Requirements," ASHVE Transactions 42, 133 (1936).

18. W. Viessman, "Ventilation Control of Odor," Annals of the New York Academy of Sciences 116, 630 (1964).

19. C. P. Yaglou, "Ventilation Requirements for Cigarette Smoke," ASHAE Transactions 61, 25 (1955).

20. C. P. Yaglou, and W. N. Witheridge, "Ventilation Requirements, Part 2," ASHVE Transactions 43, 423 (1937).

21. G. Leonardos, and D. A. Kendall, "Questionnaire Study on Odor Problems of Enclosed Space," ASHRAE Transactions 77(1), 101 (1971).

22. D. F. Owens, and A. T. Rossano, "Design Procedures to Control Cigarette Smoke and Other Air Pollutants," ASHRAE Transactions 75(1), 93 (1969).

23. W. H. Driscoll, Comment on "Ventilation Requirements," in Fresh Air and Ventilation, p. 160 (see 12 for complete reference).

24. J. E. Rush, "A Rational Basis for Ventilation," ASHVE Transactions 32, 321 (1926).

25. H. Sleik, and A. Turk, Air Conservation Engineering (Connor Engineering Corp., Danbury, CT, 1953).

26. A. Turk, "Adsorption," in A. C. Stern, Ed., Air Pollution, Vol. 4, Chap. 8 (Academic Press, New York, 1977), 3rd ed.

27. A. Turk, H. Mark, and S. Mehlman, "Tracer Gas Nondestructive Testing of Activated Carbon Cells," Materials Research and Standards 9(11), 24 (1969).

28. A. Turk, and A. Van Doren, "Fruit Storage: Saturation of Activated Carbon Used for Air Purification," Agricultural and Food Chemistry 1, 145 (1953).

29. B. W. Gamson, and R. L. Kuehner, "Composition and Method for Deodorizing Air," U. S. Patent 3, 049, 399 (1962).

30. G. F. Hanna, R. L. Kuehner, J. D. Karnes, and R. Garbowicz, "A Chemical Method for Odor Control," Annals of the New York Academy of Sciences 116, 663 (1964).

31. A. Turk, S. Mehlman, and E. Levine, "Comparative Odor Control Performance of Activated Carbon and Permanganated Alumina," Atmospheric Environment 7, 1139 (1973).

32. S. Gelfman, and A. Turk, "Air Pollutant Removal Apparatus Having Horizontal Bed for Air-Liquid Contact," U. S. Patent 3, 528, 781 (1970).

33. C. M. Bosworth, and A. J. Barduhn, "Recent Advances in Odor Control by Air Washing," Annals of the New York Academy of Sciences 116, 638 (1964).

34. K. Kulka, "Odor Control by Modification," Annals of the New York Academy of Sciences 116, 676 (1964).

35. A. Dravnieks, "A Building-Block Model for the Characterization of Odorant Molecules and their Odors," Annals of the New York Academy of Sciences 237, 144 (1974).

36. T. M. Hellman, and F. H. Small, "Characterization of the Odor Properties of 101 Petrochemicals Using Sensory Methods," Journal of the Air Pollution Control Association 24, 979 (1974).

37. L. J. van Gemert, and A. H. Nettenbreyer, Compilation of Odour Threshold Values in Air and Water (National Institute for Water Supply, Voorburg, The Netherlands, 1977).

38. W. H. Stahl, Ed., Compilation of Odor and Taste Threshold Values Data (American Society for Testing and Materials, Philadelphia, 1973).

39. A. Dravnieks, "Evaluation of Human Body Odors: Methods and Interpretations," Journal of the Society of Cosmetic Chemists 26, 551 (1975).

40. W. S. Cain, "Odor Intensity: Differences in the Exponent of the Psychophysical Function," Perception & Psychophysics 6, 349 (1969).

41. B. Berglund, U. Berglund, and T. Lindvall, "On the Principle of Odor Interaction," Acta Psychologica 35, 255 (1971).

42. T. Lindvall, "On Sensory Evaluation of Odorous Air Pollutant Intensities," Nordisk Hygienisk Tedskrift, Supplementum 2 (1970).

43. R. L. Doty, "An Examination of Relationships Between the Pleasantness, Intensity, and Concentration of 10 Odorous Stimuli," Perception & Psychophysics 17, 492 (1975).

44. H. R. Moskowitz, A. Dravnieks, and L. A. Klarman, "Odor Intensity and Pleasantness for a Diverse Set of Odorants," Perception & Psychophysics 19, 122 (1976).

45. W. S. Cain, "The Odoriferous Environment and the Application of Olfactory Research," in E. C. Carterette and M. P. Friedman, Eds., Handbook of Perception, Vol. IVA, Tasting and Smelling (Academic Press, New York, 1978), pp. 277-304.

46. M. Billot, and F. V. Wells, Perfumery Technology (Ellis Horwood Ltd., Chicester, England, 1975).

47. B. Berglund, U. Berglund, T. Lindvall, and L. T. Svensson, "A Quantitative Principle of Perceived Intensity Summation in Odor Mixtures," Journal of Experimental Psychology 100, 29 (1973).

48. B. Berglund, "Quantitative and Qualitative Analysis of Industrial Odors with Human Observers," Annals of the New York Academy of Sciences 237, 35 (1974).

49. B. Berglund, U. Berglund, and T. Lindvall, "Psychological Processing of Odor Mixtures," Psychological Review 83, 432 (1976).

50. W. S. Cain, and M. Drexler, "Scope and Evaluation of Odor Counteraction and Masking," Annals of the New York Academy of Sciences 237, 427 (1974).

51. W. S. Cain, Odor Intensity: Mixtures and Masking," Chemical Senses and Flavor 1, 339 (1975).

52. W. S. Cain, "Perception of Odor Intensity and the Time-Course of Olfactory Adaptation," ASHRAE Transactions 80(1), 53 (1974).

53. G. Ekman, B. Berglund, V. Berglund, and T. Lindvall, "Perceived Intensity of Odor as a Function of Time of Adaptation," Scandinavian Journal of Psychology, 8, 177 (1967).

54. W. S. Cain, "Odor Intensity after Self-Adaptation and Cross-Adaptation," Perception & Psychophysics 7, 271 (1970).

55. W. S. Cain, and F. Johnson, Jr., "Lability of Odor Pleasantness: Influence of Mere Exposure," Perception 7, 459 (1978).

56. D. Tucker, "Nonolfactory Responses from the Nasal Cavity: Jacobson's Organ and the Trigeminal System," in L. M. Beidler, Ed., Handbook of Sensory Physiology, Vol. 4, Part 1, Olfaction (Springer-Verlag, Berlin, 1971), pp. 151-181.

57. W. S. Cain, "Contribution of the Trigeminal Nerve to Perceived Odor Magnitude," Annals of the New York Academy of Sciences 237, 28 (1974).

58. American Conference of Governmental Industrial Hygienists, Documentation of the Threshold Limit Values for Substances in Workroom Air (ACGIH, Cincinnati, 1971), 3rd ed.

59. T. J. Kulle and G. P. Cooper, "Effects of Formaldehyde and Ozone on the Trigeminal Nasal Sensory System," Archives of Environmental Health 30, 237 (1975).

60. D. Ottoson, "Electrical Signs of Olfactory Transducer Action," in G. E. W. Wolstenholme and J. Knight, Eds., Taste and Smell in Vertebrates (J. & A. Churchill, London, 1970), pp. 343-356.

61. S. H. Katz, and E. J. Talbert, "Intensities of Odors and Irritating Effects of Warning Agents for Inflammable and Poisonous Gases," Bureau of Mines, U. S. Department of Commerce, Technical Publication No. 480 (1930).

62. W. S. Cain, "Minimum Rates of Air Intake into Buildings: Role of Odors," In J. A. J. Stolwijk, Ed., Energy Conservation Strategies in Buildings (John B. Pierce Foundation, New Haven, CT, 1978), pp. 53-70.

63. C. A. Elsberg, I. Levy, and E. D. Brewer, "The Sense of Smell. VI The Trigeminal Effects of Odorous Substances," Bulletin of the Neurological Institute of New York 4, 270 (1935).

64. W. S. Cain, "Olfaction and the Common Chemical Sense: Some Psychophysical Contrasts," Sensory Processes 1, 57 (1976).

65. R. L. Kuehner, "Humidity Effects on the Odor Problem," ASHAE Transactions 62, 249 (1956).

66. W. F. Kerka, and C. M. Humphreys, "Temperature and Humidity Effect on Odor Perception," ASHAE Transactions 62, 531 (1956).

67. J. L. Grundvig, R. E. Dustman, and E. C. Beck, "The Relationship of Olfactory Receptor Stimulation to Stimulus-Environmental Temperature," Experimental Neurology 18, 416 (1967).

68. H. Stone, "Influence of Temperature on Olfactory Sensitivity," Journal of Applied Physiology 18, 746 (1963).

69. E. Bocca, and M. N. Battiston, "Odour Perception and Environment Conditions," Acta Oto-Laryngologica 57, 391 (1964).

70. J. E. Woods, "Energy Conservation, Ventilation and Acceptable Air Quality," Proceedings of the Human Factors Society Meeting at Detroit, MI, Oct. 19, 1978.

71. W. S. Cain, "Interactions Among Odors, Environmental Factors, and Ventilation," in P. O. Fanger and O. Valbjørn, Eds., Indoor Climate (Danish Building Research Institute, Copenhagen, 1979), pp. 257-274.

72. C.-E. A. Winslow, and L. P. Herrington, "The Influence of Odor upon Appetite," American Journal of Hygiene, 23, 143 (1936).

73. National Research Council, Odors from Stationary and Mobile Sources (National Academy of Sciences, Washington, D. C., 1979).

74. A. Dravnieks, J. Whitfield, and J. Shah, "Determination of Odor Components in Tobacco Smoke," ASHRAE Transactions 80(2), 76 (1974).

75. L. Molhave, and J. Møller, "The Atmospheric Environment in Modern Danish Dwellings -- Measurements in 39 Flats," in P. O. Fanger and O. Valbjørn, Eds., Indoor Climate (Danish Building Research Institute, Copenhagen, 1979), pp. 171-186.

76. B. Berglund, and T. Lindvall, "Olfactory Evaluation of Indoor Air Quality," in P. O. Fanger and O. Valbjørn, Eds., Indoor Climate (Danish Building Research Institute, Copenhagen, 1979), pp. 141-157.

77. T. Engen, "Psychophysics 1. Discrimination and Detection," in J. W. Kling and L. A. Riggs, Eds., Woodworth and Schlosberg's Experimental Psychology (Holt, Rinehart and Winston, New York, 1971), 3rd ed., pp. 11-46.

78. A. Dravnieks, and W. H. Prokop, "Source Emission Odor Measurement by a Dynamic Forced-Choice Triangle Olfactometer," Journal of the Air Pollution Control Association 25, 28 (1975).

79. A. Dravnieks, "Threshold of Smell and Measurement," in P. E. Cheremisinoff and R. A. Young, Eds., Industrial Odor Technology Assessment (Ann Arbor Science Publ., Ann Arbor, MI, 1975), pp. 27-56.

80. L. E. Marks, Sensory Processes: The New Psychophysics (Academic Press, New York, 1974).

81. H. Fletcher and W. A. Munson, "Loudness, Its Definition, Measurement and Calculation," Journal of the Acoustical Society of America 5, 82 (1933).

82. American Society for Testing and Materials, Recommended Practice for Odor Suprathreshold Intensity Referencing - ASTM E544 (American Society for Testing and Materials, Philadelphia, 1975).

83. A. Dravnieks, "Correlation of Odor Intensities and Vapor Pressures with Structural Properties of Odorants," in R. A. Scanlan, Ed., Flavor Quality: Objective Measurement, ACS Symposium Series, No. 51 (1977), pp. 11-28.

84. T. Lindvall, and L. T. Svensson, "Equal Unpleasantness Matching of Malodorous Substances in the Community," Journal of Applied Psychology 59, 264 (1974).

85. S. S. Stevens, "Perceived Level of Noise by Mark VII and Decibels (E)," Journal of the Acoustical Society of America 51, 575 (1972).

86. H. R. Moskowitz, A. Dravnieks, W. S. Cain, and A. Turk, "Standardized Procedure for Expressing Odor Intensity," Chemical Senses and Flavor 1, 235 (1974).

87. A. Dravnieks, and P. Laffort, "Physico-Chemical Basis of Quantitative and Qualitative Odor Discrimination in Humans," in D. Schneider, Ed., Olfaction and Taste IV (Wissenschaftliche Verlagsgesellschaft MBH, Stuttgart, 1972).

88. S. S. Stevens, Psychophysics: Introduction to Its Perceptual, Neural, and Social Prospects (John Wiley & Sons, New York, 1975).

89. S. Schiffman, D. E. Robinson, and R. P. Erickson, "Multidimensional Scaling of Odorants: Examination of Psychophysical and Physicochemical Dimensions," Chemical Senses and Flavor 2, 375 (1977).

90. A. Dravnieks, F. C. Bock, J. J. Powers, M. Tibbetts, and M. Ford, "Comparison of Odors Directly and Through Profiling," Chemical Senses and Flavour 3, 191 (1978).

U.S.GPO:1980-698-169/F-124

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720