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VENTILATION REQUIREMENTS

By C. P. YAGLOU,* E. C. RILEY ** (*MEMBERS*), AND D. I. COGGINS **
(*NON-MEMBER*), BOSTON, MASS.

This paper is the result of research sponsored by the AMERICAN SOCIETY OF HEATING AND VENTILATING ENGINEERS in cooperation with the School of Public Health, Harvard University

IN a previous paper [1] Lehmberg and his co-workers outlined a technic for studying ventilation requirements from the standpoint of body odors. Their work was purely fundamental, dealing largely with the development and evaluation of a suitable scale for judging intensity of body odors, and application of this scale to a laboratory experiment for studying the factors affecting odor intensity in a confined space.

The work to be described here is an elaboration of Lehmberg's preliminary experiments. The object was to study the general problem of ventilation odors under normal conditions, comparable to those in schoolrooms, offices, homes and the like with the possibility of establishing ventilation requirements for various groups of individuals, including grade school children and adults, under representative winter and summer conditions. Three methods of odor control were studied dealing with personal sanitation, ventilation, and air washing.

PRINCIPLES OF OLFACTION

It is often stated in the literature, and rightly so, that the human nose when properly utilized affords a better criterion of the quality of air in occupied rooms than any of the known physical or chemical tests. Intelligent use of the sense of smell in ventilation requires a knowledge of its functions and limitations, a brief outline of which is given here.

The organs of smell are situated at the upper part of the nasal cavities, one in each cavity. The essential part of the organ is a delicate mucous membrane, the so-called olfactory epithelium, which covers the upper turbinal bone and

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** Assistant, Dept. of Industrial Hygiene.

[1] A Laboratory Study of Minimum Ventilation Requirements: Ventilation Box Experiments, W. H. Lehmberg, A. D. Brandt and Kenneth Morse, A. S. H. V. E. TRANSACTIONS, Vol. 41, 1935.

Presented at the 42nd Annual Meeting of the AMERICAN SOCIETY OF HEATING AND VENTILATING ENGINEERS, Chicago, Ill., January, 1936, by C. P. Yaglou.

adjacent portion of the septum (see Fig. 1), an area only about 250 sq mm.[2] The membrane is yellowish in color and is innervated by filaments from the olfactory nerve. These filaments, or olfactory hairs, are believed to be lipoid in character and they constitute the true receptive elements of the organs of smell. They are bathed in a mucous secretion from numerous olfactory glands in the epithelium. In addition to olfactory cells, there are free nerve endings in the olfactory epithelium sensitive to irritants such as ammonia or sulfuric acid, but these are believed to have little or nothing to do with true odors.

It is now generally recognized that the olfactory organs are normally stimulated by molecules of odorous substances in the inspired air diffusing to the olfactory membrane where they must enter into solution with the mucous coating of the membrane before arousing the sense of smell by chemical action on the olfactory hairs.

In ordinary respiration, the course of air passing through the nasal cavity does not extend up high enough to strike the olfactory membrane, but the odoriferous particles reach the membrane by diffusion which gradually changes the air in the olfactory cleft. Sniffing appears to be the most effective and quickest way for the full perception of odors, as it directs the air stream upwards toward the olfactory areas.

Man's sense of smell is normally aroused by inconceivably small concentrations of odoriferous substances. The sensitivity varies in different individuals. In a very recent review on odors and odor control, Pierce[3] reports that $\frac{1}{2{,}000{,}000}$ of a milligram of oil of rose per cubic centimeter of air can be distinctly smelled. Mercaptan, a liquid with a penetrating garlic odor, can be smelled in much smaller concentrations. The odor of butyric acid, a constituent of the body odor complex, can be detected in concentrations of 0.000009 milligrams per cubic centimeter of air.

The olfactory organs are quickly and easily fatigued if the exciting stimulus continues, although they can perceive the sudden appearance of new odors. The occupants of a crowded and poorly ventilated room are not capable of recognizing body odors which are very apparent or even intolerable to a newcomer. Breathing fresh air restores the sensitivity. Therefore, in order to get a good impression of ventilation conditions in a room, one should pass quickly from clean outdoor air to the room to be tested. One or two sniffs produce the strongest sensations of body odor, after which the sensation diminishes and soon ceases altogether.

Recovery of excitability is apparently likewise rapid, although it varies to some extent with the concentration and length of exposure to odorous air. In our experience with body odors, the breathing of fresh air from 5 to 10 min restores full excitability after exposure of 3 to 4 hours in crowded and poorly ventilated rooms.

For best results the nose must be neither too dry nor too moist. Persons with colds are unable to smell odors. It is possible by mixing odoriferous sub-

[2] Starling's Principles of Human Physiology, Lea and Febiger, Philadelphia, 1930.
[3] Odors and Odor Control, W. MacL. Pierce, A thesis submitted to the Department of Industrial Hygiene, Harvard School of Public Health for the Degree of Master of Science, January, 1935.

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stances in certain proportions to annul or mask their effect on the olfactory organs. Likewise, in the presence of a strong odor, one cannot, as a rule, detect a weak odor simultaneously present in the air.

The unit of odor intensity is the olfactory threshold which itself is the smallest amount of an odorous substance required to stimulate the olfactory nerves. Different odors have different threshold values, and the threshold value of an odor expressed in grams per cubic centimeter is called an olfacty.

The intensity of odor perceived by the sense of smell does not vary in proportion to the concentration but approximately in proportion to the logarithm of the concentration. The variation is according to the law of physiological stimuli in general as expressed by the Weber-Fechner law,[4] namely, Sensation $= K$ log. of stimulus-intensity.

SOURCES OF ODORS IN OCCUPIED ROOMS

Odors in living rooms come mostly from the occupants themselves. Odors from furniture, etc., are not, as a rule, conspicuous in the presence of body odors, although they may be accentuated in a warm or moist atmosphere. The

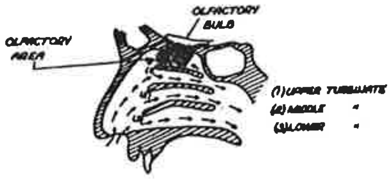

FIG. 1. SECTION THROUGH RIGHT NASAL CAVITY SHOWING OLFACTORY REGION AND DIRECTION OF AIR CURRENTS DURING INSPIRATION.

sources of body odors are numerous; foul breath, decaying teeth, sweat and sebacious secretions, especially when personal hygiene is deficient, gases from the digestive tract, and decomposition of matter from the skin and clothes are all contributory more or less, depending upon the socio-economic status of the occupants. Various gases, CH_4, CO_2, H, N, and H_2S have been detected[5] in intestinal gases eliminated from the rectum, and they may be tainted with the disagreeable odor of skatol and indol, which are normally present in the lower bowel.

Even healthy and clean persons freshly after a bath gave off in our experiments an appreciable amount of odor, which is apparently a normal waste product arising from metabolic processes and decomposition of matter in the skin and clothing.

Such odors are not, as a rule, known to be harmful, but they certainly induce a feeling of stuffiness and discomfort to anyone coming in from outside. The occupants themselves may not be conscious of the odor but they seem to be

[4] On the determination of Odors and Tastes in Water, G. M. Fair, *Journal New Eng. Water Works Assn.*, Vol. 47 (Sept., 1933).
[5] The Health of the Industrial Worker, E. L. Collis and Major Greenwood, P. Blakiston's Son & Co., Philadelphia, 1921.

capable of detecting stuffiness or lack of freshness in the air. Sensitive persons are occasionally affected in a pathological way by sitting in such rooms. The untoward effects of body odors on appetite for food and performance of physical work were studied extensively by Winslow and Palmer in the laboratories of the New York State Commission on Ventilation.[6]

Despite the opposing schools of thought concerning the health aspects of body odors, the general agreement is that they should be controlled preferably by personal habits of cleanliness, or by ventilation and air conditioning, as it is difficult to control the source of odor itself. According to the latest views the air of occupied rooms should give a favorable impression on entering, taking into consideration such factors as odors, freshness, temperature, humidity, drafts and other factors affecting the senses. The present paper is largely concerned with such primary, as well as secondary sense impressions, which were taken as a criterion of ventilation requirements.

EQUIPMENT

The experiments were carried out in two adjoining rooms, on the northwest side of the building. The rooms were approximately identical, having a floor area of 155 sq ft, a ceiling height of 9 ft 2½ in., a window area of 20 sq ft and a net air space of 1410 cu ft approximately. The windows were weather-stripped and all cracks carefully sealed with adhesive tape.

One of the rooms, hereafter referred to as the experimental room, was occupied by the subjects who constituted the source of odor production. The other room served as a control room for the judges who estimated the odor intensity in the experimental room.

A small tight door was cut in the common partition to allow direct passage of the judges from the control room to the experimental room in order to judge the odor intensity and air quality. Separate air conditioning units, installed in the corridor, kept the two rooms at approximately the same temperature and humidity in any given test, so that the only variable factors in the two rooms were the outdoor air supply and the number and type of occupants.

One of the air conditioners was equipped with a centrifugal humidifier capable of fully saturating the air passing through it under the experimental conditions. The other one was of the conventional spray-dehumidifier type. The rated capacity of both was 1000 cfm, but the orifices employed for measuring airflow reduced it to about 500 cfm, which was ample for the purpose of the experiments. The air was introduced to the rooms near the ceiling through 14 in. round ducts running along the entire length of the rooms and fitted with splitters. The ducts were perforated over half of the periphery with a multitude of holes ½ in. in diameter and 2½ in. on centers, facing toward the ceiling. The recirculated air was withdrawn at floor level through a 10 in. round duct. The exhaust air was allowed to escape to the corridor through sensitive check louvres attached near the bottom of the doors.

Accurate measurements of the total air supplied to the rooms, the amount recirculated, and that taken from out of doors, were made by means of thin-

[6] Ventilation. Report N. Y. State Commission on Ventilation. E. P. Dutton & Co., New York, 1923.

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plate orifices designed in accordance with the A. S. M. E. standards[7] and checked against a calibrated venturi meter. Control of the air flow was by means of variable speed motors and different size orifices.

Dry- and wet-bulb temperatures were measured by means of aspirating psychrometers, and the air movement by means of kata-thermometers, or globe anemometers.[8] Measurements of carbon dioxide were made by means of a 20 cc modified Haldane gas analysis apparatus[9] for CO_2 only.

EXPERIMENTAL PROCEDURE

Starting with a more or less definite plan, the procedure had to be modified during the first few experiments in order to allow for unforeseen conditions. During the preliminary part of the study, the outdoor air supply to the control room was fixed at the usual standard of 30 cfm per person with no recirculation. It was soon found out, however, when we began to study the influence of air space, that the odor strength in the control room was often higher than that in the experiment room. This upset the comparisons as it is physiologically impossible to judge odor strength by comparing an odor of standard intensity with one of lower intensity. The difficulty was overcome by increasing the outdoor air supply to 50 cfm per person and limiting the number of judges in the control room at any one time to 3, usually 2. This control standard was based on the minimum outdoor air supply required to keep the odor intensity in the control room approximately at the olfactory threshold, by comparison with clean outdoor air. The departure from the original plan is a happy one, as the olfactory threshold is a unit of odor intensity, and a much more rational base line than the arbitrary 30 cfm standard. The situation is analogous to our standards of sound or noise, in which the base line is likewise the threshold of hearing, that is a barely audible sound.

The experimental room was occupied by 3, 7, and 14 subjects in different series of experiments, so as to obtain 3 different floor areas per person, *i.e.*, 11, 22, and 52 sq ft and 3 different air spaces 100, 200 and 470 cu ft approximately. The air flow in the experimental room was varied from about 2 to 30 cfm per person in different experiments. In one series the total air supply remained constant at 30 cfm per person but the amount taken from out of doors was varied from 2 to 30 cfm. In another series only outdoor air was circulated through the experimental room. In a third series, the mixture of outdoor and recirculated air was washed, cooled, humidified or dehumidified in order to determine the effect of these processes on odor removal and on minimum ventilation requirements.

Keeping the air flow in the control room at 50 cfm per person in all experiments and the temperature and humidity approximately the same as that prevailing in the experimental room, the judges passed one at a time from the control to the experimental room, once every hour or so, recording the strength

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[7] Fluid meters and their application. Report of Comm. on Fluid Meters. Research Publication, *Am. Soc. Mech. Engrs.*, 3rd ed., 1931.
[8] A new instrument to be described elsewhere.
[9] Methods of Air Analysis, J. S. Haldane and J. I. Graham, Charles Griffin & Co., Ltd., London, 1935.

of body odor immediately after the change, according to the scale in Table 1. The agreement between judges was usually within ±½ point on the scale, as in Lehmberg's work, once they have become familiar with the scale.

Altogether 60 men and women with more or less normal sense of smell served as judges. They were drawn from employees of the school and graduate students. Two of the judges devoted their whole time to the tests. The others usually from 8 to 15 in each test were called in when needed, and after a short stay in the control room, they passed to the experimental room to smell the air, and were then released. All records were kept confidential by two men who ran the tests.

As a rule each test consumed a whole morning (9-12:30) or a whole afternoon (1:30-5:00). In a few instances the duration was shorter or longer.

TABLE 1. SENSORY INTENSITY SCALE OF BODY ODOR

ODOR INTENSITY INDEX	CHARACTERISTIC TERM	QUALIFICATION
0	None	No perceptible odor.
½	Threshold	Very faint, barely detectable by trained judges; usually imperceptible to untrained persons.
1	Definite	Readily detectable by all normal persons but not objectionable.
2	Moderate	Neither pleasant nor disagreeable. Little or no objection. Allowable limit in rooms.
3	Strong	Objectionable. Air regarded with disfavor.
4	Very strong	Forcible, disagreeable.
5	Overpowering	Nauseating.

The equilibrium time with respect to odor intensity varied from one to three hours, inversely with the amount of outdoor air introduced.

Before and after each test the rooms were thoroughly ventilated in order to get rid of residual odors, and the air conditioning apparatus was kept clean at all times.

In order to secure uniformity in results and at the same time cover a fair cross-section of socio-economic status, the subjects were divided in 5 groups as follows:

(a) Sedentary men and women of average socio-economic status (between 16 and 60 years old), including high school, college and medical students, office workers, teachers, housewives, etc. (total 177).

(b) Grade school children between 7 and 14 years old of average or balanced socio-economic status (total 62).

(c) Laborers, such as janitors and street workers (total 8).

(d) School children of the poorest class (total 7).

(e) School children of the better class (total 28).

Most of the subjects belonged to groups *a* and *b*. They were apparently healthy and had normal personal habits. Variations from the normal were

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studied in a limited number of subjects classified under groups *c*, *d*, and *e*. Some of the children in groups *b*, *d*, and *e* were selected by the principal and nurse of a nearby school and sent to the tests with their teacher.

All subjects were paid adequately to keep them interested in the work. No attempt was made to control personal habits of hygiene or nutrition. However, the use of cosmetics, including face powder, had to be forbidden owing to a masking effect upon odors. Individual variations did occur, even among persons of apparently the same socio-economic status and with the same number of baths, but these were smoothed off by the use of a large number of subjects, as would be the case in most public buildings.

During the experiments the subjects were seated comfortably in arm chairs, and they read, wrote or played cards. The clothing was of the customary indoor type according to the season.

The age, height, sex and occupation were recorded routinely in all tests. The date of last bath was also recorded more or less regularly, but this record was optional in the case of women. The weight was accurately determined before and after each test. At the beginning, near the middle and at the end of each test the adult subjects recorded their impressions of comfort, humidity, air quality and odor, according to a simple plan explained to them at the beginning of the test. The children answered questions pertaining to comfort only.

In this way information was obtained dealing with both primary and secondary impressions of air quality under various conditions of ventilation and with representative groups of persons. The primary impressions were those of the judges; the secondary, those of the subjects after becoming adapted to the conditions of the tests.

RESULTS

The data presented in this progress report deal with more or less comfortable conditions of temperature and humidity in the winter and summer. Observations with high and low humidities and with temperatures near the upper and lower boundaries of the comfort zones are yet to be completed. In addition many other questions are now being studied, bearing on the subject matter and data under consideration, for presentation in a final paper.

Throughout this work during the past three years, advantage has been taken of the splendid opportunities offered for parallel *sideline* studies of problems dealing with seasonal variation of comfortable air conditions in large groups of children and adults, sudden temperature contrasts, insensible perspiration, carbon dioxide output, humidity and air freshness, etc., which will be published in the future as time permits.

The mass of data in the present paper is condensed to essential facts in Table 7, and the reader who is interested in facts alone may save much time by referring to this tabulation.

Intensity of Body Odor in Relation to Outdoor Air Supply

(a) Observations with sedentary subjects.

In Fig. 2 are shown the results of experiments with simple ventilation using healthy sedentary subjects over 16 years of age. The data are representative of winter conditions when the air is simply tempered and circulated through the occupied space with or without recirculation. Ordinates in Fig. 2 give the average odor intensity recorded by the judges in each test under equilibrium conditions. Abscissae give the corresponding quantity of outdoor air supplied per person per minute. In most instances the total air supply was 30 cfm per person (black circles) part of which (X) was taken from outdoors and the remaining part (30-X) was recirculated. The white circles represent tests in which there was no recirculation.

The first thing to notice in Fig. 2 is that when the odor intensity as perceived by the sense of smell is plotted against the logarithm of the outdoor air supply

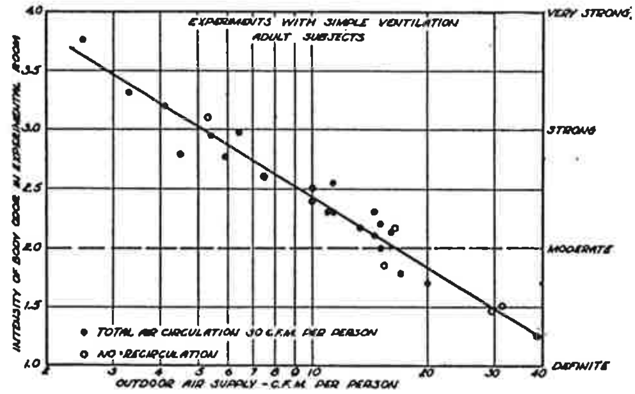

FIG. 2. OUTDOOR AIR SUPPLY IN RELATION TO ODOR INTENSITY. NET AIR SPACE PER PERSON, 200 CU FT

the relationship is linear. This is in accord with the Weber-Fechner law of physiological reactions in general, namely,

$$\text{Sensation} = K \log. \text{ of stimulus}$$

and by inference

$$\text{Odor intensity index} = K \log. \text{ of concentration of odor, or}$$

$$\text{" \quad " \quad "} = K \log. \frac{1}{\text{outdoor air supply}} \text{ . and}$$

$$\frac{(\text{O.I.})_1}{(\text{O.I.})_2} = \frac{\log. \text{cfm}_2}{\log. \text{cfm}_1}$$

Translated into words, the strength of body odor perceived by the sense of smell on entering an occupied room from relatively clean air varies inversely as the log. of the outdoor air supply. The same fundamental law applies to the sense of hearing, and it may be of interest to call attention to the fact that our standards for noise and sound have been determined by similar subjective tests using the normal human ear for criterion.

It is seen in Fig. 2 that the body odor was very strong and disagreeable when the outdoor air supply per person was under 3 cfm, the strength decreasing arithmetically as the air supply increased logarithmically. The minimum air supply required to dilute the odor to the allowable intensity of 2 under the

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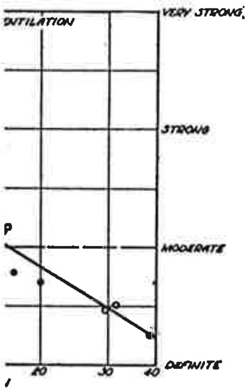

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given conditions (200 cu ft air space per person, no air conditioning) is about 16 cfm per person. With 30 cfm per person, the odor is still readily detectable but not objectionable.

Recirculation does not seem to affect the odor strength appreciably, as shown by the black and white circles in Fig. 2. In other words, from the standpoint of body odor, a room can be ventilated just as well with an outdoor air supply of 16 cfm per person as with a total supply of 30 cfm, about ½ of which is recirculated. Recirculation is often desirable for adequate distribution and temperature control, but one of the disadvantages is that it smells up the ducts, fans, etc., and unless the system is flushed frequently with clean air, higher air quantities will be needed to obtain satisfactory results.

Sex was not a factor in odor intensity and ventilation requirements in all instances in which female subjects used no perfumery of any sort, including face powder, before coming to the tests. Results of two series of experiments

TABLE 2. INTENSITY OF BODY ODOR WITH MEN AND WOMEN SUBJECTS UNDER COMPARABLE CONDITIONS

SUBJECTS	NUMBER OF TESTS	TOTAL NUMBER OF SUBJECTS	AIR SPACE PER PERSON CU FT	AVERAGE OUTDOOR AIR SUPPLY PER PERSON CFM	AVERAGE ODOR INTENSITY
Women.....	4	23	200	15.8	2.05
Men........	5	35	200	15.9	2.00

with men and women subjects, under comparable conditions are shown in Table 2. Similar tests with grade school boys and girls showed no appreciable difference in odor intensity that could be attributed to sex.

(b) Observations with children of average class.

Grade school children between 7 and 14 years old have, apparently, an equation of their own. In spite of smaller body surface and lower total metabolism, they give off more odor than the adults and the air requirement is therefore considerably greater. The upper curve in Fig. 3 shows the results on a group of children of average or balanced socio-economic status. The conditions of the experiments were more or less comparable to those in schoolrooms with respect to air space, method of ventilation, activity, etc. The lower curve is reproduced from Fig. 2 for comparison with the results of adults under similar conditions. Whereas in the case of adults an outdoor air supply of 16 cfm per person was sufficient to take care of objectionable body odors, in children the air supply had to be increased to 21 cfm per child.

(c) Observations with adolescent children.

Adolescent boys and girls between the ages of 16 and 20 years yielded results closer to those of adults than those of grade school children. In 4 experiments, with a total of 28 adolescent boys and girls, using an air flow of about 10.5 cfm per person, the odor intensity averaged 2.5 ± 0.13, as compared with 2.4 for the adult subjects (See Fig. 2) and 2.7 for the grade school children (See

Fig. 3) under identical conditions. It may therefore be assumed that the requirements of adolescent children and adults are practically the same.

Air Space, Odor Intensity and Ventilation Requirements

(a) Observations with sedentary adult subjects.

The number of persons occupying a room appears to be a very important factor affecting odor intensity and air requirement as shown in Fig. 4. The 3 curves represent results with 3, 7, and 14 subjects in the room, corresponding to floor areas of 11, 22, and 52 sq ft per person and air spaces of 100, 200, and 470 cu ft respectively. The middle curve is reproduced from Fig. 2 without the points.

With 470 cu ft of air space per person, which is more or less representative of conditions in homes, uncrowded offices, and the like, the air requirement

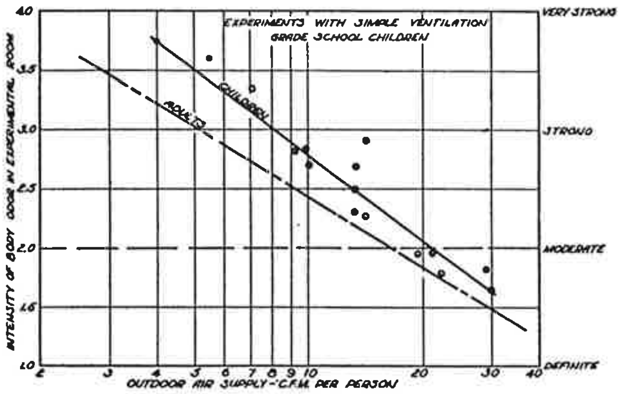

FIG. 3. OUTDOOR AIR SUPPLY IN RELATION TO ODOR INTENSITY. NET AIR SPACE PER CHILD, 200 CU FT

from the standpoint of body odor was 7 cfm per person; with 200 cu ft air space, it was about 16 cfm per person, and with 100 cu ft air space, it was almost 25 cfm or 3½ times as great as with an air space of 470 cu ft.

With constant air supply the intensity of body odor varied inversely with the log. of the air space. The relationship is shown in Fig. 5 from which it is possible to compute the ventilation requirements for intermediate densities of occupancy. There is no way to tell, except by actual tests, whether the values would hold with ceiling heights much greater than 10 ft, as for instance in theaters. The diffusion characteristic may be different there.

(b) Observations with children of average class.

Fig. 6 shows a similar picture with children as subjects. Comparison with Fig. 5 will reveal again higher odor intensities and air requirements in children than in adults in all 3 series of experiments. The ventilation requirements for children corresponding to the allowable odor intensity of 2 are

12	cfm	per	child	with	470	cu	ft	air	space
21	"	"	"	"	200	"	"	"	"	and
29	"	"	"	"	100	"	"	"	"

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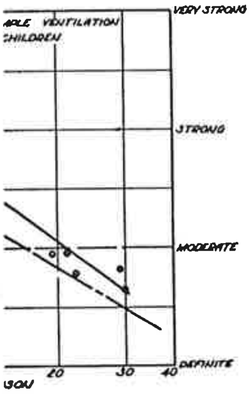

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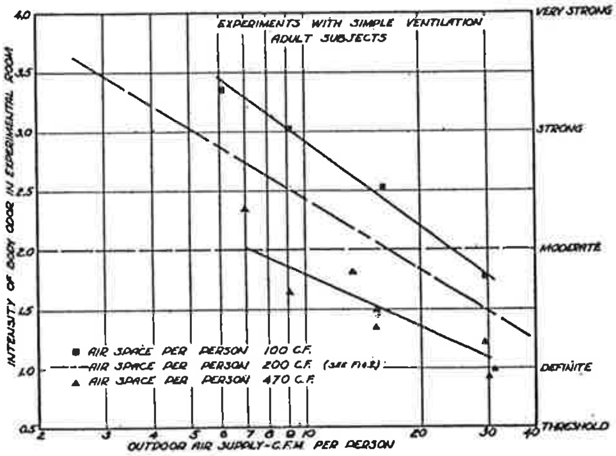

FIG. 4. INFLUENCE OF AIR SPACE ON ODOR INTENSITY. ADULT SUBJECTS

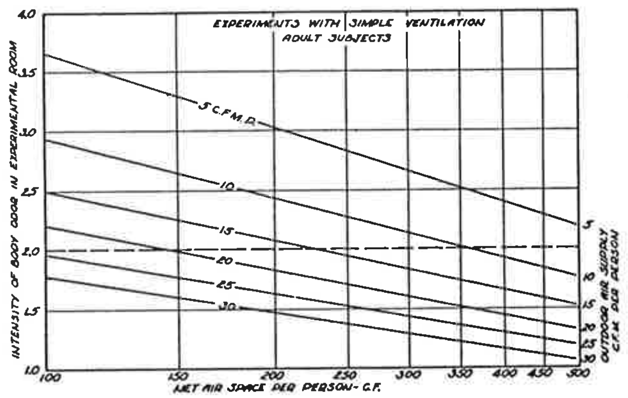

FIG. 5. CHART FOR COMPUTING VENTILATION REQUIREMENTS OF SEDENTARY ADULTS FROM THE STANDPOINT OF BODY ODOR

Example: Given an air space of 300 cu ft per person, follow vertical line through given air space until it meets the broken horizontal line passing through the allowable odor intensity of 2. The required outdoor air supply per person is 12 cfm obtained by interpolation.

as compared with 7, 16, and 25 cfm respectively for adults. Values for intermediate air spaces may be computed from Fig. 7.

The Influence of Air Conditioning Processes on Odor Intensity and Ventilation Requirements

The usual methods of washing, humidifying or cooling recirculated air were found to remove a considerable amount of odor, thus making it possible to reduce the outdoor air supply. Three different arrangements were studied, as follows:

(a) mixture of outdoor and recirculated air passed through a conventional spray-type dehumidifier for cooling and dehumidifying the air of the experimental room in warm weather.

(b) mixture passed through a centrifugal humidifier, for humidifying the air in cold weather.

(c) mixture passed over a surface cooler through which cold water between 35 and 50 deg was circulated. The cooler used in these experiments was capable

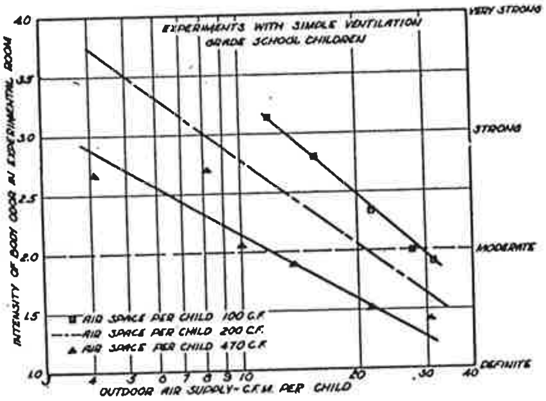

FIG. 6. INFLUENCE OF AIR SPACE ON ODOR INTENSITY. CHILDREN SUBJECTS

of lowering the temperature of the air passing over it (210 cfm) through a maximum of about 10 deg.

All 3 series of observations were carried out with 7 subjects in the experimental room (200 cu ft air space per person) and with a total air circulation of 210 cfm, or 30 cfm per person. The temperature range of the cold spray water and of the water circulated through the cooler was between 35 and 50 deg in different experiments. In the case of the centrifugal humidifier the range was 40-55 deg. In order to make the conditions uniform the spray water was changed before each test and the water tanks of the apparatus cleaned out periodically.

Fig. 8 shows the results. The top curve is again reproduced from Fig. 2 for comparison with the results of simple ventilation, that is with sprays and surface cooler off. The surface cooler absorbed the least amount of odor and the dehumidifier the most. The absorption by the centrifugal humidifier was but only slightly greater than that of the surface cooler. In all instances the surface of the cooler was wet with condensation which dripped to the humidifier tank below and overflowed to the sewer.

The outdoor air requirement was correspondingly reduced from 16 cfm per person with simple ventilation to about 13 cfm per person when the mixture of outdoor and recirculated air was passed through the centrifugal humidifier or

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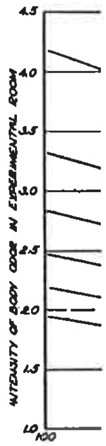

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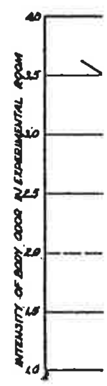

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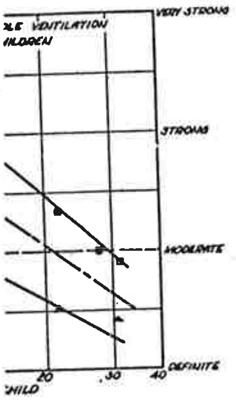

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over the surface cooler, and to less than 4 cfm per person when the mixture was passed through the spray dehumidifier. In the last instance the odor intensity appears to be almost independent of the outdoor air supply. The performance of the dehumidifier may be more appreciated by calling attention

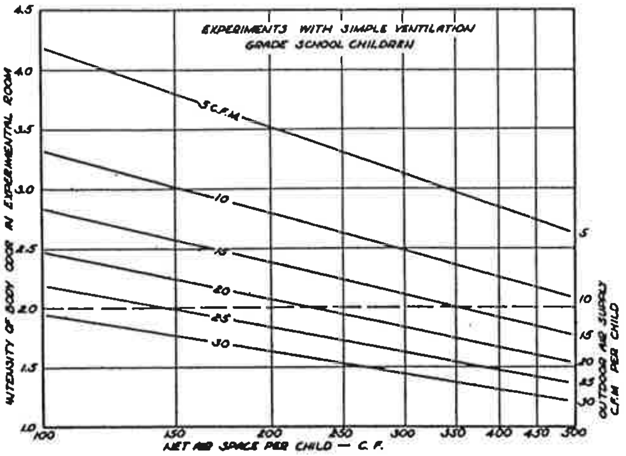

FIG. 7. CHART FOR COMPUTING VENTILATION REQUIREMENTS OF GRADE SCHOOL CHILDREN FROM THE STANDPOINT OF BODY ODOR. EXAMPLE IN THE USE OF CHART SHOWN IN FIG. 5

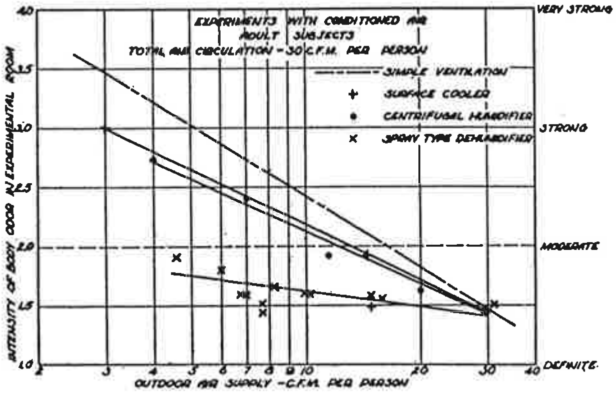

FIG. 8. ODOR REMOVING CAPACITY OF VARIOUS AIR CONDITIONING PROCESSES. NET AIR SPACE PER OCCUPANT, 200 CU FT

to the fact that the odor intensity cannot be lowered much below 1.5 when the total air circulation is limited to 30 cfm per person, even with a cleaner efficiency of 100 per cent (see Fig. 8). A possibility of olfactory delusion, rather than true odor absorption, cannot be entirely discounted.

While the results obtained with the surface cooler and centrifugal humidifier will probably be realized in actual practice under similar operating conditions, the striking performance of the dehumidifier may be more or less limited by the following factors. The rated capacity of the dehumidifier spray system was about 15 gal per minute per 1000 cu ft of air circulated, but under the conditions of the experiments (210 cfm) the actual pumping rate corresponded in most instances to about 70 gpm per 1000 cu ft of air circulated. The unusually large pumping rate is probably not an important factor, as in a few tests in which the rate was reduced to the nominal 15 gpm per 1000 cu ft of air, the odor intensity was substantially identical with that of the higher rate. Undoubtedly there is a critical pumping rate, but the data are not sufficient at present to warrant a definite statement.

More important appears to be the cleanliness of the spray water, and water-storage capacity of the dehumidifier tank. In most of the experiments under consideration cold water was pumped to the sprays from a separate brine water-cooler having a storage capacity of 310 gal. The capacity of the dehumidifier tank itself was 10 gal. Another pump returned warm water from the dehumidifier tank to the brine water cooler. It is evident that the odor absorbed by the spray water was greatly diluted, owing to the unusually large water capacity of the brine cooler, and this presumably increased the odor removing capacity of the dehumidifier. The situation may be analogous in the case of large installations in which the spray water is cooled in a separate Baudelot cooler having a large storage capacity. Other factors at work appear to be the degree of flushing of the eliminator plates and the temperature of the spray water itself.

The importance of clean fresh water may be appreciated by the results of an experiment using old water from a previous test, after standing in the brine cooler and dehumidifier tank for 8 days. The outdoor air supply was 12.7 cfm per person, and the average odor intensity rose to 2.10, instead of 1.55 according to Fig. 8. This was the highest odor intensity ever recorded in any of our experiments with the spray dehumidifier. A few subjects in the room were conscious of a *musty* odor in the air even after remaining in the room 3½ hours.

Socio-Economic Factors in Relation to Odor Intensity, and Ventilation Requirements

The observations in Figs. 2 to 8 deal with groups of individuals of average or balanced socio-economic status and habits of personal hygiene. In a special series of experiments an attempt was made to study maximum variations from the average by using a limited number of subjects of the poorest and best class. With adult subjects the two extremes were represented by laborers (janitors and street workers), and medical students. In the case of school children the principal and nurse of a nearby school selected two groups, and the authors selected a third one from a different district, a group of children given daily baths and the best of care.

The results of these experiments are presented in Table 3. It will be noted that with equal ventilation rates, the laborers gave off considerably more odor than the medical students, and the ventilation requirements should therefore be greater. The computed air flow necessary to reduce the odor intensity to the

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TABLE 3. SOCIO-E

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Average Sedentary Adult Subject (See Fig. 2)..........
Grade School Children of Poorest Class..........
Grade School Children of "Better Class"..........
Average Grade School Child (See Fig. 3)..........
Grade School Children of Best Class
Average Grade School Child (See Fig. 5)..........

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allowable limit of 2 is 23 cfm per laborer and 15.5 cfm per medical student, an excess of about 50 per cent. The air requirement of the medical students appears to be but slightly less than that of the whole group of sedentary adult subjects (See Fig. 2) probably because the majority of the subjects were medical students.

The probable ventilation requirements were computed in the following manner: If the three lines in Figs. 4 and 6 are extended to zero odor intensity,

TABLE 3. SOCIO-ECONOMIC STATUS, BATHS, ODOR INTENSITY, AND VENTILATION REQUIREMENTS

Experiments with Simple Ventilation

Type of Subjects	Total Number of Subjects	Air Space per Person Cu Ft	Outdoor Air Supply per Person Cfm	Average Odor Intensity	Computed Ventilation Requirements Cfm per Person	Last Bath Average Number of Days
Laborers..........	7	200	7.3	3.29	24	7.2
Laborers..........	7	200	14.4	2.40	22	7.4
Average for Laborers	...	...	...	...	23	7.3
Medical Students..	7	200	7.5	2.60	15	1.3
Medical Students..	7	200	14.5	2.11	16	1.2
Average for Medical Students........	...	...	...	...	15.5	1.25
Average Sedentary Adult Subject (See Fig. 2)..........	..	200	...	...	16	2.2
Grade School Children of Poorest Class............	7	200	22.0	2.83	38	8.0
Grade School Children of "Better Class"...........	14	200	20.9	1.87	18	3.0
Average Grade School Child (See Fig. 3)...........	..	200	...	...	21	4.2
Grade School Children of Best Class	14	100	16.4	2.34	22	0.8
Average Grade School Child (See Fig. 5)...........	..	100	...	...	29	4.9

they would all meet approximately on the horizontal scale at about 150 cfm. If now the experimental data of Table 3 are plotted on a chart similar to Figs. 4 or 6, a line joining each of the given points with the common point at 150 cfm would represent the probable relationship under the given conditions. The intersections of these lines with a horizontal line passing through the allowable odor intensity of 2 would then give the probable ventilation requirements under the various conditions.

In a similar manner the requirements of school children were found to vary from 18 to 38 cfm per child, according to socio-economic status, and this reflected objectively upon the bathing habits of individuals as can be seen in the last column of Table 3. To make sure about this point a group of children of average class and a group of medical students were tested separately, within about a day after a bath and complete change of underwear, and a week later, with no baths or change of underwear in between. The data are summarized in Table 4.

To begin with, the ventilation requirement of the children was about 10 per cent in excess of the medical students, but after about a week the difference

TABLE 4. BATHS, ODOR INTENSITY AND VENTILATION REQUIREMENTS

Experiments with Simple Ventilation

Type of Subjects	Air Space per Person 200 Cu Ft		
	Outdoor Air Supply Cfm per Person	Average Odor Intensity	Computed Ventilation Requirement Cfm per Person
Grade School Children			
0.5 Days after Bath and Complete Change of clothing	14.2	2.26	18
6.5 Days after Bath	14.3	2.90	29
Medical Students			
1.2 Days after Bath and Change of Underwear	14.5	2.11	16
7.0 Days after Bath	16.6	2.18	20

increased to 50 per cent approximately, owing presumably to the greater liability of children's clothing becoming soiled, and probably to other factors.

The significance of baths to ventilation requirements may be better appreciated by plotting the data of Tables 3 and 4 on a chart as in Fig. 9. The last two cases at the bottom of Table 3 have been omitted, as the air space differed from the others. The outstanding point in Fig. 9 is that, once the minimum ventilation requirements are fixed for any given conditions, the problem of body-odor control resolves itself to personal factors of hygiene and sanitation. Unfortunately the ventilating engineer has no control upon these factors; as a rule he has to accept the conditions as he finds them and design his system accordingly.

Another important point in Fig. 9 is that the proverbial weekly bath is not at all adequate from the ventilation standpoint, particularly in the case of school-children. Two baths a week would help a great deal in solving the schoolroom odor problem. Unfortunately, there are homes of poor families with no bathing facilities at all. In a group of seven children of the poorest class, 3 frankly volunteered the information that they had to go to a club for their bath once every two weeks or so.

A worthwhile experiment from the standpoint of both economy and èducation would be to have grade schools in the poorer districts provided with baths and in this way treat the real cause with, perhaps, less expenditure of money, than would be the case with costly ventilation, which after all is temporarily corrective, not preventive. The mothers would then have more time to attend to the laundry of the children's clothing.

AIR QUALITY IN RELATION TO AIR SUPPLY AND ODOR INTENSITY

In discussing subjective impressions of air quality from the standpoint of air supply, two different viewpoints must be taken into consideration (*a*) that of the visitor upon entering a room from clean air and (*b*) that of the occupant

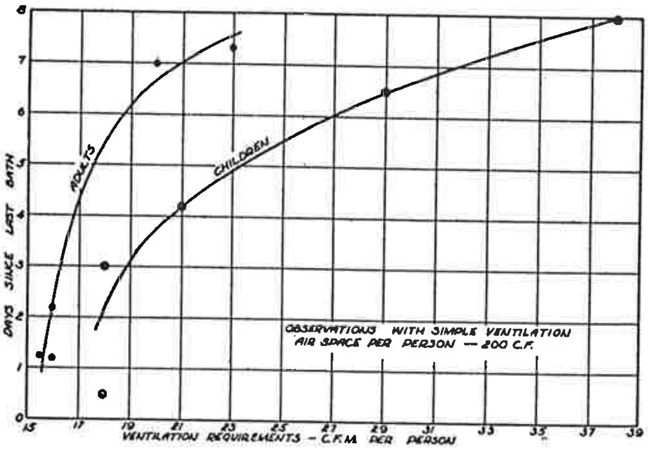

FIG. 9. EFFECT OF BATHS ON VENTILATION REQUIREMENTS. REQUIREMENTS BASED ON AN ALLOWABLE ODOR INTENSITY OF 2

after having become adapted to the conditions of the room. This suggests two ventilation standards both of which are valuable, the choice depending upon the nature of the ventilation problem.

In the present study the primary impressions of air quality were those of the judges; the secondary those of the subjects after exposures of 3½ hours to the air conditions under investigation. The primary or judges' impressions of air quality depended largely on odor intensity when both temperature and humidity conditions in the rooms were suitable.

The quality scale had five grades; *excellent, good, fair, poor,* and *bad,* and also a provision for a negative answer such as *cannot tell.* Air with an odor intensity of 1 was invariably qualified as good or good minus, odor intensity 2 corresponded to fair or fair to good, 2.5 was poor to fair, 3 bad, and 4 very bad. The correspondence was so close that it was found unnecessary to question the judges about air quality. Figs. 2 to 8 may therefore be utilized for illustrating approximately the relationship between primary impressions of air quality and outdoor air supply, by substituting impressions of air quality for odor intensity on the vertical scale.

The subjects, on the other hand, could not, as a rule, detect the odor, except when there were 14 of them in the room. Even then however only about a third remarked about odors and the majority in this third were not at all certain whether it was body odor or odors of some other kind. The subjects' criterion of good air was a *freshness complex* perceived by the nose. The most popular reasons for poor air quality, under comfortable conditions of temperature and humidity, were variously described as *stuffiness, closeness, heaviness, lack of freshness,* etc.

Upon entering the room at the beginning of the tests the subjects generally agreed that the quality was good or excellent. The next record near the middle of the test showed a depreciation of quality, and the third record at the end of the test showed but minor changes from the second. Most of the observations on air quality came from college and medical students, an intelligent group of persons capable of analyzing their feelings and voting quite concordantly. Observations from other groups were on the whole less consistent, except under extreme conditions. They could tell definitely when the air was good or poor but as a rule they could not discriminate intermediate grades. Sometimes the answers were negative, such as *cannot tell.*

The quality of air in the control room was always good or excellent (excepting tests in which the temperature was too high or too low), and there was no depreciation of quality throughout the period of the tests. This is to be expected with a constant outdoor air supply of 50 cfm per person in all experiments.

In the classification of the data shown in Table 5, all observations in which the subjects were warm or cold have been excluded, in order to restrict the relationship, as much as possible, to factors pertaining to air quality and outdoor air supply. The results are shown graphically in Fig. 10 which was constructed by evaluating grades of air quality in terms of numbers.

It will be observed that with simple ventilation and with 200 cu ft air space per person, the air quality was poor to bad when the air supply was under 3 cfm per person, improving rapidly as the air supply increased to 15 cfm. Beyond this point further increases in the ventilation rate had little or no effect on air quality, from the standpoint of the occupants, and it will be recalled that from the standpoint of the judges the odor was not objectionable with airflows in excess of 16 cfm (Fig. 2). The general trend is similar, when the air space is reduced to 100 cu ft per person, but the air quality is inferior throughout, a situation which is consistent with the higher odor intensity reported by the judges (Fig. 4).

With an air space of 470 cu ft, on the other hand, air quality appears to be practically independent of air supply, in so far as the occupants are concerned, when the period of occupancy does not exceed 3½ hours. An outdoor air supply of 7 cfm per person was ample from the standpoint of both subjects (Fig. 10) and judges (Fig. 4). The same was more or less true when the air was cooled and dehumidified by passing through the dehumidifier as shown in Figs. 10 and 8.

Table 6 gives additional observations of air quality, those recorded by the attendant or teacher in the children's experiments. These data are necessarily limited because each test yielded a single observation only, that of the attendant or teacher. In experiments with 3 children, observations of air quality had to be omitted as the children were unattended.

To check this apparent close correspondence between primary impressions of odor intensity and secondary impressions of air quality we plotted the values

TABLE 5. AIR QUALITY, OUTDOOR AIR SUPPLY, AND ODOR INTENSITY

Impressions of Subjects After Exposure of 3½ Hours to Comfortable Conditions of Temperature and Humidity

Outdoor Air Supply Cfm per Person	Mean Air Supply Cfm per Person	Mean Odor Intensity[a]	Total Number of Subjects	Air Quality Number of Subjects Recording: Excellent (5)	Good (4)	Fair (3)	Poor (2)	Bad (1)	Mean Air Quality
	Simple Ventilation Tests. Air Space per Person 200 Cu Ft								
Under 3	2.5	3.75	7	..	..	1	3	3	1.7
3–5	3.7	3.21	25	..	1	18	5	1	2.8
5–7	5.7	3.08	33	..	3	22	8	..	2.9
7–10	8.7	2.91	14	..	5	8	1	..	3.3
10–15	13.9	2.20	42	1	29	12	..	..	3.7
15–17	15.8	2.02	27	4	16	7	..	..	3.9
29–31	29.7	1.54	15	3	10	2	..	..	4.0
38.7	38.7	1.25	6	..	6	..	..	..	4.0
	Simple Ventilation Tests. Air Space per Person 470 Cu Ft								
7–9	8.1	2.00	6	..	4	2	..	..	3.7
13–16	14.6	1.55	9	..	6	3	..	..	3.9
29–32	30.3	1.11	6	..	5	1	..	..	3.8
	Simple Ventilation Tests. Air Space per Person 100 Cu Ft								
6.1	6.1	3.37	14	..	..	4	8	2	2.1
16.0	16.0	2.52	14	..	6	5	3	..	3.2
29.4	29.4	1.78	14	2	5	7	..	..	3.6
	Experiments with Spray Dehumidifier. Air Space per Person 200 Cu Ft								
4–7	6.1	1.72	24	..	14	10	..	..	3.6
7–10	8.4	1.56	26	..	14	12	..	..	3.5
10–15	12.5	1.59	14	..	11	3	..	..	3.8
31.2	31.2	1.51	7	2	3	2	..	..	4.0

[a] Impressions of judges upon entering room from relatively clean air of threshold odor intensity.

of these two variables, appearing in Tables 5 and 6, against one another, as shown in Fig. 11. It can be seen that the factors of air supply, air space, as well as those pertaining to individual differences and to air conditioning processes, almost disappear from the picture, indicating that an underlying factor in air quality, when both temperature and humidity are controlled, is the odoriferous organic matter given off by the human body. This is in spite of the fact that the subjects themselves could not smell the odor. Air flow, air space, air conditioning processes, and personal sanitation, are apparently secondary factors affecting the concentration of the odoriferous matter.

In the Study of the N. Y. State Commission on Ventilation, Winslow and Palmer [10] arrived at a somewhat analogous conclusion from an entirely different angle. Quoting from their original report,—"these experiments seem to warrant the conclusion that there are substances in the air of an unventilated occupied room (even when temperature and humidity are controlled) which in some way and without producing conscious discomfort or detectable physiological symptoms diminish the appetite for food. The observed beneficial effects of fresh air may to some extent be connected with this phenomenon."

TABLE 6. AIR QUALITY, OUTDOOR AIR SUPPLY, AND ODOR INTENSITY

Impressions of Attendant or Teacher in Children's Experiments after Exposure of 3½ Hours (Observations with Simple Ventilation)

Outdoor Air Supply Cfm per Person	Mean Air Supply Cfm per Person	Mean Odor Intensity	Number of Observations	Mean Air Quality
	Air Space per Child 200 Cu Ft			
Under 6	4.8	3.67	2	2.5 (Poor to Fair)
10–15	13.0	2.48	5	3.4 (Fair to Good)
19–23	21.1	1.91	4	3.8 (Good)
30	30.0	1.65	2	4.0 (Good)
	Air Space per Child 100 Cu Ft			
15.7	15.7	2.80	1	3.0 (Fair)
21.8	21.8	2.34	1	3.5 (Fair to Good)
31.5	31.5	1.90	1	4.0 (Good)

CARBON DIOXIDE IN RELATION TO OUTDOOR AIR SUPPLY AND ODOR INTENSITY

Since the time of Max von Pettenkofer, about 75 years ago, the carbon dioxide content of air in occupied rooms has been widely used as a measure of fresh air supply and a convenient yardstick for the degree of air vitiation by products of organic decomposition from the human body. The value of this index in ventilation work has often been questioned by many workers, and recently by Houghten [11] who showed that changes in the moisture content of air in occupied rooms constitute a more reliable and convenient index of air supply than CO_2 itself. Houghten did not, however, measure the actual CO_2 content of air in his experiments but he computed it from approximate metabolic relationships.

In the present study the actual CO_2 in the air was determined in most experiments near the end of the tests, at different stations inside the experimental

[10] Effect Upon Appetite of the Chemical Constituents of the Air in Occupied Rooms, C.-E. A. Winslow and G. T. Palmer, *Proc. Soc. Biol. & Med.*, vol. 12, p. 141 (1914-15).

[11] Indices of Air Change and Air Distribution, F. C. Houghten and J. L. Blackshaw, A. S. H. V. E. TRANSACTIONS, Vol. 39, 1933.

room or in the exhaust leading to the corridor. The relationship between CO_2 and outdoor air supply is given in Fig. 12. The curve was drawn from the well known formula

$$\text{Cfm per person} = \frac{100}{CO_2 - 3.5}$$

where 3.5 is approximately the average value of CO_2 in parts per 10,000 as found in the air entering the apparatus before mixing with recirculated air.

Although the theoretical curve roughly averages the experimental points, great discrepancies occur in the steep portion of the curve which happens to

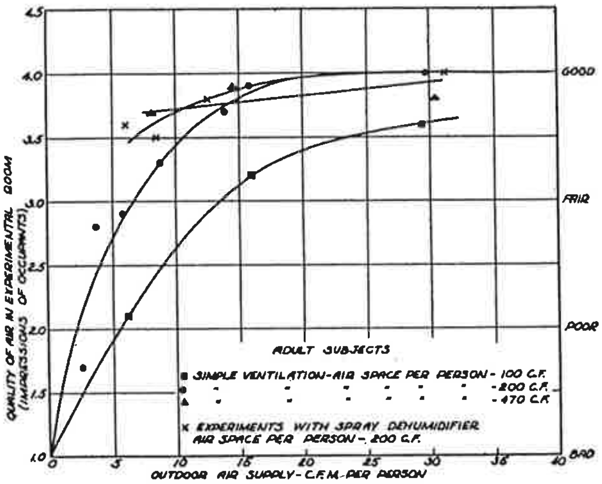

FIG. 10. AIR QUALITY IN RELATION TO OUTDOOR AIR SUPPLY UNDER VARIOUS CONDITIONS. IMPRESSIONS OF OCCUPANTS (SUBJECTS) AFTER EXPOSURES OF 3½ HOURS TO THE SPECIFIED CONDITIONS

be the practical range used in ventilation work. For example, a CO_2 of about 9 parts per 10,000 may mean an actual ventilation rate between 15 and 30 cfm per person, or a maximum error of 100 per cent, depending largely upon the amount of CO_2 given off by the particular group of occupants in the room. The curve is so steep for ventilation rates above 10 cfm, that even small individual variations in CO_2 output correspond to large variations in the air supply. The usual errors in determining CO_2 add to the discrepancies.

For airflows under 10 cfm per person, the discrepancy is not so great, but the computed air flow from the equation is almost always higher than the actual airflow, owing presumably to absorption of CO_2 by the walls, furniture, clothing, etc., when the concentration is high.

As an index of body odor CO_2 appears to be still worse, as can be gathered from the dispersion of the experimental points in Fig. 13. The reasons are quite obvious. Suppose, for instance, that a person takes no bath for a week or two, the odor intensity would be considerably increased (see Fig. 9) but

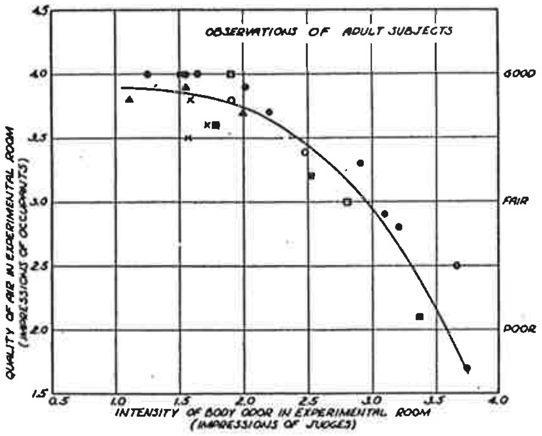

Fig. 11. Relationship Between Primary Impressions (Judges') of Odor Intensity and Occupants' Impressions of Air Quality After Exposures of 3½ Hours. Solid Points Represent Observations of Adult Subjects; Hollow Points Are Observations of Attendant or Teacher in Children's Experiment. Legend Shown in Fig. 12

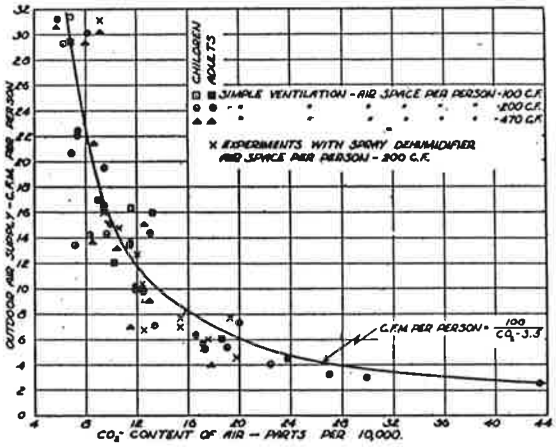

Fig. 12. Carbon Dioxide Content of Air in Experimental Room in Relation to Outdoor Air Supply

the CO_2 output would barely be affected. Children, for example, in spite of their low CO_2 excretion give off more odor than the adults (Fig. 13) owing largely to differences in bathing habits and cleanliness of clothing, as has been related. On the other hand, when recirculated air is passed through an air-washer, the water removes a considerable portion of the odoriferous matter without affecting much the concentration of CO_2 (Fig. 13).

In the light of these and other similar data by the New York State Commission on Ventilation, and others, it is evident that 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

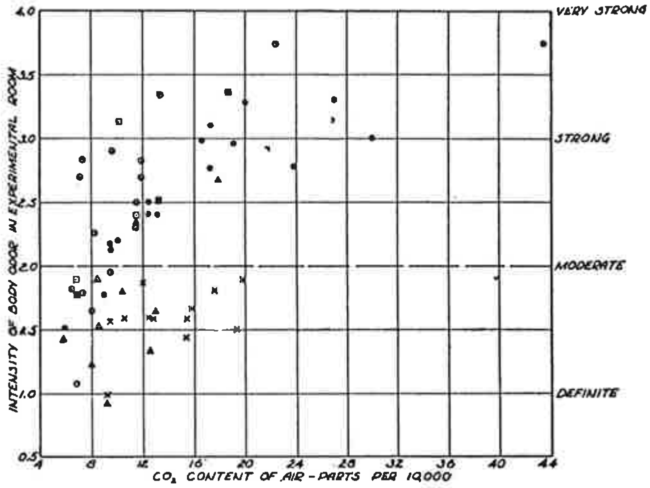

FIG. 13. CARBON DIOXIDE CONTENT OF AIR IN EXPERIMENTAL ROOM IN RELATION TO ODOR INTENSITY. FOR LEGEND SEE FIG. 12

under 10 cfm per person. Factors pertaining to air distribution can be studied much easier by variations of temperature and air movement from station to station than by variations of CO_2, as outlined in the AMERICAN SOCIETY OF HEATING AND VENTILATING ENGINEERS GUIDE (1935, p. 51).

THE A. S. H. V. E. AND OTHER EARLIER STANDARDS

In Table 7 are summarized the ventilation requirements under various conditions as determined in the present study. The impossibility of fixing any single value that would apply under all conditions is evident. Each case would have to be considered on its own merits. The A. S. H. V. E. provisional standard of 10 cfm per person seems to be a more or less fair average value for adult persons where the air space per occupant is between 250 and 500 cu ft per occupant. It falls far too short in grade schools attended exclusively by children of poor districts, assuming that the results are representative, and somewhat too long when the air is cooled and dehumidified in a spray-type air conditioner.

Likewise the results of the present study are not necessarily contradictory to those of the old masters (De Chaumont, Parkes, Billings, and others). The

TABLE 7. SUMMARY OF MINIMUM OUTDOOR AIR REQUIREMENTS FOR VENTILATION UNDER VARIOUS CONDITIONS

(Provisional Values Subject to Revision upon Completion of Work)

TYPE OF OCCUPANTS	AIR SPACE PER PERSON CU FT	REQUIREMENTS BASED ON PRIMARY[a] IMPRESSIONS CFM PER PERSON	REQUIREMENTS BASED ON IMPRESSIONS OF OCCUPANTS[b] CFM PER PERSON
Heating Season with or without Recirculation. Air Not Conditioned.			
Sedentary Adults of Average Socio-Economic Status	100	25	23
Sedentary Adults of Average Socio-Economic Status	200	16	11
Sedentary Adults of Average Socio-Economic Status	300	12	..
Sedentary Adults of Average Socio-Economic Status	500	7	>5
Laborers	200	23	..
Grade School Children of Average Class	100	29	..
Grade School Children of Average Class	200	21	15
Grade School Children of Average Class	300	17	..
Grade School Children of Average Class	500	11	..
Grade School Children of Poor Class	200	38	..
Grade School Children of Better Class	200	18	..
Grade School Children of Best Class	100	22	..
Heating Season. Air Humidified by Means of Centrifugal Humidifier. Total Air Circulation 30 Cfm per Person.			
Sedentary Adults	200	12	..
Summer Season. Air Cooled and Dehumidified by Means of a Spray Dehumidifier. Total Air Circulation 30 Cfm per Person.			
Sedentary Adults	200	>4[c]	6[c]

[a] Impressions upon entering room from relatively clean air at threshold odor intensity. Allowable odor intensity = 2. (For scale, see Table 1).
[b] Corresponding to an air quality of fair to good.
[c] Values provisionally restricted to the conditions of the tests.

differences in the requirements between then (50 to 30 cfm per pupil) and now (Table 7) are accountable by differences in standards of personal sanitation, as Fig. 9 would seem to indicate.

In the light of the present study, two sets of requirements are suggested as shown in Table 2 to serve two different purposes. In buildings with transient occupants, such as theaters, banks, restaurants, and the like, where the primary impression of the patrons upon entering is of considerable importance, the higher requirements would be better suited in spite of the higher cost. On the other hand, in homes, offices, schools, etc., the lower or secondary requirements may be more desirable from the economic standpoint. Lacking values in Table 7 will be completed soon and weak data will be strengthened and revised in accordance with additional work. The important omission of information on winter air conditioning will also be attended to.

It should be clearly understood that the requirements in Table 7 are average values determined by averaging impressions of a large group of persons. Individual variations will naturally occur; there will always be a few persons who would prefer somewhat higher standards as well as a few others who would be content with lower standards.

Given the specifications of minimum outdoor air requirements under various conditions, the problem would then resolve to recirculating a sufficient amount of air when needed in order to maintain proper temperature, humidity, and air movement. Temperature, in fact, is one of the most important factors in air quality and unless it is controlled the quality will suffer badly no matter what the outdoor air supply, particularly when the air is overheated.

SUMMARY

1. The outdoor air requirements for ventilation under comfortable condition of temperature and humidity have been determined from primary impressions of odor intensity upon entering occupied rooms and from impressions of the occupants themselves after exposures of 3½ hours to the conditions investigated.

2. Wide individual variation occurred in the amount of odor emitted by various groups of persons, according to socio-economic status, especially the bathing habits of individuals and cleanliness of clothing. Children, as a rule, gave off more odor than adults, and their bathing habits were deficient.

3. Even healthy clean persons freshly after a bath gave off an appreciable amount of odor which required from 15 to 18 cfm of outdoor air per person in order to dilute it to a concentration that was not objectionable to persons entering the room from relatively clean air. A week after a bath the ventilation requirement of children increased from 18 to 29 cfm, as compared with an increase of from 15 to 20 in the case of adults.

4. With a given group of occupants the intensity of body odor perceived upon entering a room from relatively clear air (air with threshold odor intensity) varied inversely with the logarithm of the quantity of outdoor air supplied and the logarithm of the air space allowed per person.

5. Untreated recirculated air in any amount had no effect on odor intensity or quality of air.

6. The usual processes of washing, humidifying, cooling, and dehumidifying recirculated air apparently removed a considerable amount of body odor and, under certain conditions, practically the maximum amount possible by the use of known processes.

7. Under comfortable conditions of temperature and humidity, both primary and secondary impressions of air quality were found to be related closely to the concentration of odor in the air, despite the fact that the occupants themselves could not smell the odor.

8. Based upon these impressions, two sets of ventilation requirements were derived for various groups of individuals under various conditions as summarized in Table 7. The impossibility of fixing any single standard that would apply under all conditions is clearly evident. Each case, it would seem, must be considered on its own merits.

9. The concentration of CO_2 in the air of occupied rooms proved to be an unreliable index of ventilation, from the standpoint of both outdoor air supply and odor intensity.

ACKNOWLEDGMENT

Most of the preliminary painstaking work was done by Messrs. J. W. Buford, Gayle Priester, and Joseph Gessner, to whom the authors are greatly indebted.

DISCUSSION

J. D. CASSELL: This paper is of particular interest to me as it strengthens the conclusions of the Pennsylvania State Committee appointed to study and report on rules to govern air supply to public school classrooms. At the start of our work the State Committee adopted the report of the Ventilation Standards Committee of this Society, by providing 10 cu ft of outside air, and 20 cu ft of recirculated air per occupant of room. These proportions were found insufficient to eliminate offensive odors; so after further investigation the Committee finally agreed on 15 cu ft of outside air and 15 cu ft recirculated air per minute per occupant of room. This final report has not been made public, probably due to a change in state administration.

I wish to congratulate Professor Yaglou, not only on this most thorough and enlightening paper, but also in the masterly manner in which he presented it. I hope to hear comments from other school men present. By the way, I am no longer a school man; there comes a time in some men's life when they just can't take it, and I am one.

N. W. DOWNES: This paper brings to mind an experience we had in Kansas City some years ago. We built a 30-room elementary school in the north end of the city for serving children such as Professor Yaglou referred to as coming from the more unfortunate class. The building was equipped with a warm blast fan system, with air washer, automatic temperature and humidity control and so dampered that not only outside air in toto could be used but air could be recirculated on a basis of one-third, two-thirds or in toto, the air supplied remaining constant at 30 cfm per pupil. We soon found we were getting no place on a recirculation basis on account of odors which were at times nauseating. Even the use of outside air in toto failed to eliminate the objections.

The Principal on investigation soon found that a large number of these youngsters were sent to school by their parents literally sewed up for the winter. He immediately took it upon himself to change the situation by requiring each child to take a warm shower bath once a week at the school, although encountering vigorous opposition from some of the parents. The objectionable odors soon disappeared as did also the objections from the parents. Afterwards it was found possible to recirculate through the air washer as much as two-thirds of the total without objectionable odors.

G. P. ELLIS: In Pittsburgh we continue to use 30 cfm per pupil. However, in schools now being built and in operation since September 1, we have equipment whereby we can recirculate 50 per cent, but the control of that equipment and the capacity of the equipment is such that we can adjust it up to 30 cfm whenever we feel like it, and feel it is necessary to do so.

J. N. HADJISKY: I do not represent Detroit officially, but I know the conditions there as they existed during the period 1920 to 1928. The practice during that time was to circulate 30 cfm per person. The percentage of recirculated air is dependent on outside temperature. A fair average for the cold winter period was 50 per cent. In some of the schools in the outlying subdivisions, outside of the city limits, it was a common practice, in very cold weather, to close the fresh air dampers altogether. Naturally the odors in the rooms were very noticeable.

I made a test once in a small school, with a ventilating system handling 30,000 cfm. If the fresh air dampers were closed for half hour, the odors become very noticeable, in spite of the continual washing of the 100 per cent recirculated air.

I should like to ask Professor Yaglou a question in connection with his tests when expanded surface coils were used. Some years ago when I was testing some air cooling units, I noticed that the units having direct expansion coils and adjusted to keep the coils just frost covered, the unit did not keep the air in the room as fresh as when the room was cooled with the unit using cold water as the cooling medium in the coils. In this last case the wetted surface of the coil seemed to have a better cleansing effect upon the recirculated air than the dry, frost covered coil, of the direct expansion type. The condensation which was collected, showed by its color that it had a great deal of dirt and color.

MR. SHEPHERD: I would like to ask Professor Yaglou if the water used in the spray type dehumidifier was fresh or had been used long enough to become saturated relative to the odors.

S. R. LEWIS: To say that 50 per cent or 20 per cent of the air delivered to a school room is outside air and that the balance is recirculated air means very little in practical service because ducts and walls are so porous and leaky that no exact or consistent measurement is possible. The recirculated part of the air may be badly contaminated or it may be uncontaminated even though it has traversed the room.

The distribution of the air within the room so that each occupant shall receive his share of the entering air has a very great deal to do with the problem. Suppose that actually 25 per cent outside air and 75 per cent recirculated air are introduced. If each person receives his share there may be no evidence of odor or of improper heat removal. However, there are the ever-present conditions of poor distribution, dead corners, down drafts from cool windows, and up drafts from warm surfaces, which create turmoil and which render the equal distribution of the air a complex matter.

There is in my experience neither odor trouble nor temperature control trouble attending partial recirculation but I doubt whether the exact amount of contact with contaminated air can be measured or expressed as a percentage unless the room and ducts are bottle-tight.

MEMBER: The water used in the air washers of the Chicago Public School systems is supplied continuously fresh. A ¾-in. pipe runs into the tank while the air is being recirculated, and a certain level is maintained for overflow. A great number of our troubles originate with odors in connection with these systems.

J. J. AEBERLY: It is not gracious at this time for a committee member to make a critical analysis of the report his chairman submits. For this reason I would like to make only a few friendly remarks.

This is a very significant paper. The air conditioning engineer has recognized the importance of the need for control of odors in ventilating systems. I have had occasion to investigate a number of air conditioning jobs a long time after the engineer had completed his work. Without exception, the problem today in these systems is the elimination of odors.

I would like to say, Professor Yaglou, that it would be well to make some intensive study of the effect of air-washers, particularly those systems where dew point control is used and similar controls where the water is recirculated. It may be that under these conditions the effectiveness of air-washers will not be as great, although I think your findings are substantially correct for non-recirculated water. I think you will all agree with me that Professor Yaglou did a mighty fine piece of work.

W. H. DRISCOLL: I think this is one of the finest contributions to the literature of this Society we have had in many a day. Those of us who worked on the Ventilation Standards Committee, know how difficult was the problem of arriving at a decision as to what we should set up as the minimum outdoor air requirement.

I think that Committee worked for well on to two years, possibly more than two years, before it had its report in final shape for submission to this Society. I venture to say that nine-tenths of the time we spent in debate and discussion was spent in a consideration of the question of air volume, and outdoor air requirements.

When we 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 aggressive 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.

The work that Professor Yaglou has done has helped materially to bring out the necessity of some outdoor air. I am quite sure that it will galvanize into activity the Committee on Ventilation Standards which has been inactive for some time, primarily because we wanted the standards that we had set forth to circulate, to be tried out, to get the reactions that might come from them. I think that Professor Yaglou deserves our gratitude and I want at this moment to pay my personal tribute to him for what he has done, and the great work he has always done for this Society. I have every confidence in the findings and conclusions arrived at by him in the investigations he makes. I know something of his work. I keep in close contact with him, and I feel that he has given us something to work on that we have never had before in the history of ventilation.

MEMBER: I am particularly interested in the length of time these occupants were exposed. It would have a direct bearing on the results.

MR. HAAS: I was interested in the tremendous effect the per cubic foot of space of occupant had on the total air circulated. In totaling the values given in this paper it will be noted that six times as much air per hour is required, if it is circulated in a small space, as if one sixth of the amount of additional space in the volume of the room is provided. What difference does it make whether the air is in the room, or circulated?

E. V. FINERAN: It appears to me on the air washer chart that the curve is drawn with the wrong slope. This curve indicates that a bad odor condition would never be reached, yet if it is extrapolated on the other end, an infinite quantity of outside air is required to approach a basic level.

J. H. VAN ALSBURG: This is a fine paper because it presents basic information, which has a direct and practical application. I have just one suggestion, namely, I hope that the Committee and the investigations will continue to cover one more series of conditions, such as the requirements for bed rooms in hotels, in homes and in railroad sleeping cars.

Dr. E. V. Hill: I cannot let the opportunity go by to have my say on this subject. I want to agree with Mr. Aeberly about the importance of the subject of odors. It is a thing I seldom do is to agree with Mr. Aeberly, but I will in this case.

The paper is good; it is giving us information that we need, but it seems to me that we could get more fundamental information if we approached the problem in a little different way.

If I want to know how much air is required to remove the odors from a human being, I would test the amount of odors given off by a human being nude, without any clothes on. Then I would put the clothing in a cabinet and see how much air was required to remove odors from the clothes. In that way you would have some fundamental information.

I did not hear Professor Yaglou mention the character of the clothing worn by the different subjects, and it seems to me that this is a very important thing. I have expressed myself on this subject before, and some one always gets up and says, "Well, we don't have our children nude in school, or people nude in theaters. Why test nude subjects?" It is the same old subject. It is the same thing that applies in our work on the effect of temperature, or whatever the temperature is that produces comfort. We want to know fundamentally how the air affects the human body. We want to know in this particular case how much air is required to remove the odors given off by normal healthy clean human bodies.

Professor Yaglou indicated the fallacy in the presentation by showing the difference in the air requirement after the children were washed, so it seems to me that we should get away from this silly old idea we have got to experiment with normally clothed people. The doctor doesn't examine a patient with the clothing on. He would be laughed out of the profession. Why should we do physiological experimental work with the subjects clothed. Let us get down to a scientific basis, and do our experimental work in this where we are dealing with the physiological effects of air on nude subjects, and find out how clothing modifies the picture.

Mr. Driscoll: Somebody always gets up and disagrees with Dr. Hill so I don't want to disappoint him. I am concerned primarily with people who are clothed, and the circumstances under which we as engineers have to treat those people.

W. F. Christman: This discussion refers to the idea that we have a bare room, with no draperies, rugs, or things of that nature. What effect on the recommendation that Professor Yaglou makes has the question of draperies or rugs or any odor-giving device of that nature? All of the discussion up to this time seems to be concerned with the odor question. I would like to know if there is any effect on the bacteriological count with regard to the amount of outside air introduced.

Mr. Aeberly: Although this paper clearly indicates that the results obtained with air-washers are based on non-recirculation of the wash water, this fact should be emphasized because in practice similar results are ofttimes expected, but are not obtained when wash waters are recirculated.

Professor Yaglou: I agree with you, Mr. Aeberly; in our experiments the spray water was recirculated but it was changed in every experiment. Also a greater amount of water was sprayed per unit volume of air handled, than in commercial air washers.

A common question has been the effect of water purity of the air washer. This was an important factor, and one or two of you probably missed it in the paper. You will find on page 146 the importance of keeping the water fresh, that is changing the water in the air washer every day, or as, in our case, after every experiment.

Exposure in all experiments was 3½ hours as indicated on the slides. In most instances it was not necessary to continue the experiments that long, but we did, nevertheless. Equilibrium was established in one to three hours, depending on the air space per person and amount of outside air introduced to the room.

I fail to understand Mr. Haas' question. In our experiments, the minimum air space per occupant was 100 cu ft, and the maximum, 470 cu ft. The corresponding ventilation requirements were 25 and 7 cfm per person respectively. In other words, decreasing the air space per occupant to about one-fifth, increased the ventilation requirements three and a half times, not six times, as Mr. Haas' question would seem to imply. Perhaps I misunderstood his question.

In regard to Mr. Fineran's question, he probably overlooked the fact that the air-washer chart holds for a total air circulation of 30 cfm per person, as shown clearly on the chart (Fig. 8). Increasing the total air circulation through the washer beyond 30 cfm per person would increase the odor-absorbing capacity of the washer, and the washer curve in Fig. 8 would fall below the present curve parallel to it. It is reasonable to assume that at some point beyond 30 cfm the odor of water acquired by the air in passing through the washer might predominate and mask the body odor, thus setting a limit to the deodorizing action of the washer.

In reply to Mr. Christman's question, odors emanating from rugs and furnishings in a room may not be conspicuous in the presence of body odors, or may themselves mask the body odor depending on their relative strength. There is no doubt that a certain minimum amount of air is necessary to remove odors from furnishings in rooms occupied by few persons. In many instances natural infiltration is sufficient for this purpose.

The quantitation and qualitative relationships between air-borne bacteria in occupied rooms and amount of outdoor air supply is now being studied by Dr. Wells at the Harvard School of Public Health.

AIRFOIL FA

By W. A. Ro

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* Mechanical Engineer.
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