

SOME METHODS OF MEASURING VENTILATION

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(With 5 Figures in the Text)

INTRODUCTION

Measurement of ventilation is of importance both in the design and control of heating and ventilating systems. In addition, the rates of ventilation actually obtaining constitute an important factor in any quantitative studies of air-borne infection. Measurements of ventilation have, however, not been made as often as was desirable: partly, at least, owing to the lack of a convenient method.

In principle the ventilation of any room may be determined by measuring the volumes of air entering and leaving. In practice this may be difficult or impossible, and even with controlled plenum systems it is usually desirable to check how far the ventilation is in fact controlled. The alternative method of determining ventilation is to distribute in the air of the room some vapour or particulate smoke as a tracer substance and to estimate the rate at which it disappears.

If the air in the room is continually and completely mixed with the incoming air, then the rate of disappearance

$$-\frac{dc}{dt} = \frac{v}{V} c$$

and

$$c = c_0 e^{-Rt},$$

or

$$R = \frac{2.30}{t} (\log_{10} c_0 - \log_{10} c),$$

where c is the concentration of the tracer substance remaining after time t (c_0 the concentration at time $t=0$), v is the volume of air entering and leaving the room of volume V in unit time, and R , defined as v/V , is the ventilation rate in air changes per unit time, usually the hour.

A substance, to be suitable for this purpose, must be stable in air and not removed from the air of the room at a measurable rate by any process other than ventilation. If measurements are to be made in an inhabited room, which is often desirable, it must be non-toxic, and as far as possible odourless at the concentration necessary for measurement.

If the mixing of the incoming air with the air of the room is not sensibly complete the concentration of tracer substance will not, in general, decay logarithmically nor will the rate of decay be the

same in various parts of the room. In practice, however, it is usually possible to fit a curve of the type

$$c = c_0 e^{-Kt} \quad (\text{where } K \text{ is a constant})$$

to the observations within the limits of experimental accuracy. The decay constant K may be either greater or less than the rate of air change R , according to the disposition of the air circulation in the room relative to the point at which the observations were made. This 'constant' may conveniently be referred to as the equivalent ventilation at the point of measurement.

If c be replaced in the above equation by \bar{c} , the average value of the concentration remaining in the room after time t , a 'constant' \bar{K} can be obtained which may be said to represent the equivalent ventilation of the room as a whole during the measurement. In practice it is not usually feasible to attempt to evaluate this quantity, and the measurements will be made at a selection of positions in the room, chosen to give as representative a picture as possible and suitable to the purpose of the investigation. If a fan is used, and this is effective in mixing the air of the room, the equivalent ventilation determined as above should be identical throughout the room and equal to R . This is often a convenient measurement to make, especially as R is often otherwise unknown, but need not bear any simple relation either to \bar{K} or the equivalent ventilation at any point in the absence of the fan.

Previous workers (see Warner, 1940) have generally employed carbon dioxide or hydrogen, both of which substances fulfil admirably the conditions necessary for a tracer substance, but have considerable disadvantages in convenience and portability. Gas cylinders are cumbersome, and the use of town gas, when available, is not without disadvantages.

METHODS DESCRIBED IN THIS PAPER

Several methods of estimating ventilation employing a variety of tracer substances have been tried in this laboratory and a number have proved useful in field work. The principal considerations which

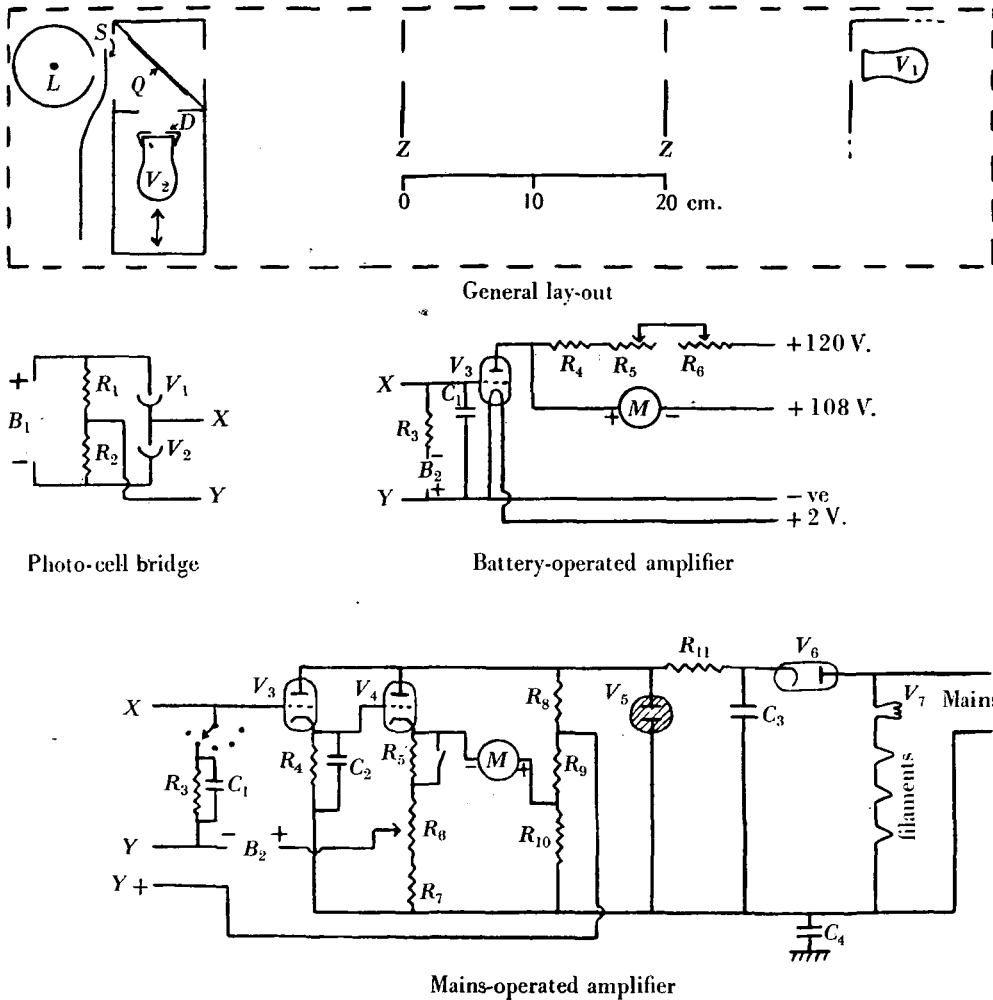


Fig. 1. *General lay-out.* L, 125 W. mercury arc; S, shutter; Q, quartz plate; D, diaphragm stop; V₁, V₂, cadmium vacuum photo-cells; Z, Z, screens to prevent arc being visible in room.

Photo-cell bridge. V₁, V₂, cadmium vacuum photo-cells with quartz window, type UDG7; R₁, R₂, 4 megohms each; B₁, 45 V. deaf-aid battery.

Battery-operated amplifier. V₃, PM2HL; M, 0-50 μA.; B₂, 1.5 V. battery; C₁, 0.01 μF. mica; R₃, 100 megohms; R₄, 5000 ohms; R₅, 5000 ohms; R₆, 500 ohms.

Mains-operated amplifier. V₃, H63; V₄, H30; V₅, S130, voltage stabilizer; V₆, U31; V₇, 301, baretter; B₂, 1.5 V.; M, 0-1 mA.; C₂, 0.01 μF.; C₃, 16 μF.; C₄, 1 μF.; Y+, extra connexion for use with single photocell without external battery; R₃, series of values up to 1000 megohms; C₁, mica, high insulation, 10⁵/R 3 μF., i.e. when R₃=1000 megohms the value of C in parallel will be 10⁵/10⁹=0.0001 μF.; R₄, 500,000 ohms; R₅, 100 ohms, normally shorted; open switch to check amplifier sensitivity; R₆, 500 ohms; R₇, 2000 ohms; R₈, R₉, 5000 ohms each; R₁₀, 1000 ohms; R₁₁, 2000 ohms, 10 W.; Mains, 200-250 V. a.c. or d.c. When connected to a.c. mains it is desirable that the negative side of the amplifier be connected to the neutral lead. A choke condenser suppressor in the mains lead may be helpful in eliminating the effect of switch transients and other similar phenomena. B₂ is inserted to minimize the loss in sensitivity due to the relatively high resistance of the dropping chain R₈, R₉, R₁₀. In both amplifiers resistors may be 1 W. types, except where otherwise specified. It should be obvious that special care must be taken with the insulation and screening of all points directly connected to X.

led to the development of these particular methods were that the apparatus should be readily portable and self-contained. This was achieved by using as tracers easily volatile substances which could be estimated at very low concentration in the air. The methods may be summarized before being discussed individually in detail:

(i) Estimation of the vapour concentration by means of its ultra-violet absorption.

absorption of 5–10 % (in a light path of convenient length) at 2537 Å. with a suitable organic vapour at a concentration which would fulfil the necessary conditions discussed in the introduction, and a portable absorption meter was designed and constructed capable of estimating an absorption of 10 % in a 50 cm. path length to an accuracy of 1 %, i.e. to ± 0.1 % of the total incident light. (50 cm. was chosen as the maximum path length

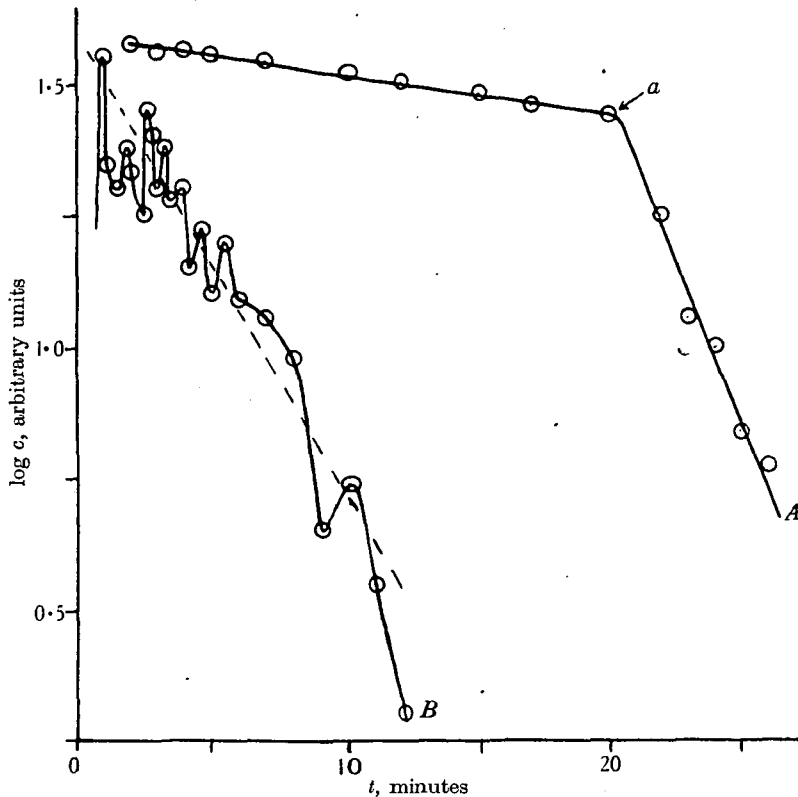


Fig. 2. A. 4.5 c.c. of ethyl acetoacetate evaporated from a hot plate into a 4500 cu.ft. room, doors and windows shut. Air continually mixed by a 12 in. table fan. Equivalent ventilation in centre of the room 1.1 turn-overs/hr. After 20 min., at point *a*, an exhaust fan extracting approximately 1800 cu.ft./min. from the room was switched on. Equivalent ventilation in centre of room 25 turn-overs/hr. (Air changes introduced by fan approximately 24/hr.) B. 2 c.c. of acetyl acetone evaporated from a hot plate into a room of 3750 cu.ft., doors and windows shut, but a strong south-west wind (about 35 m.p.h.) blowing against windows. No mixing fan in room. Average equivalent ventilation at centre of room, broken line, 13 turn-overs/hr.

(ii) Absorption of the vapour from a measured volume of air and colorimetric estimation of the resulting solution either photoelectrically or by visual comparison.

(iii) Determination of the vapour concentration by the rate of development of a colour on a treated test paper.

(i) *Estimation by ultra-violet absorption*

A preliminary examination of the recorded data suggested that it should be possible to obtain an

obtainable in an easily portable single piece of apparatus, and 10 % is the maximum absorption found practicable in this path with any of the possible organic vapours tested.) The lay-out of this, together with the electrical circuits, is shown in Fig. 1. Cadmium vacuum photo-cells with quartz windows were used, since they are almost completely insensitive to visible light; and although their overall sensitivity is low it is adequate at wave-lengths below 2900 Å., where absorption takes place.

In operation the meter is first adjusted to zero with no light falling on either of the photo-cells; the shutter is then opened and the position of V_2 adjusted to return the current to zero. This will be when the photoelectric current produced in V_2 by the light reflected from the 45° quartz plate equals that produced in V_1 by the transmitted light. Once the adjustment has been made readjustment of the position of V_2 is only occasionally necessary. The light path to V_2 is minimal and 50 cm. shorter than that to V_1 , so that the presence in the air, which can circulate freely between Q and V_1 , of any substance having an absorption in the ultra-violet

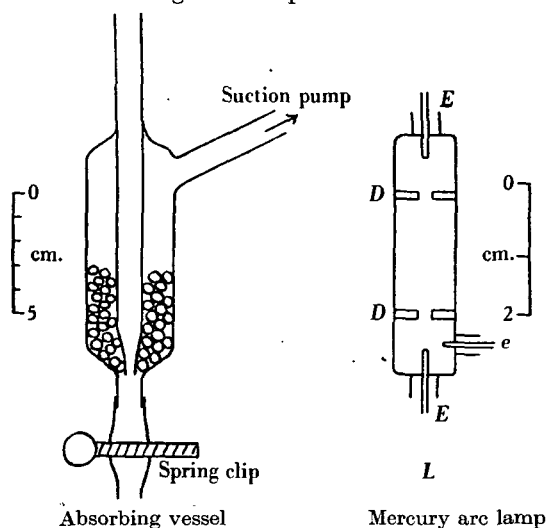


Fig. 3. *Absorbing vessel.* Made from pyrex glass; pyrex beads desirable, but not essential. Diameter of jet, not critical, 2–3 mm. *Mercury arc lamp.* E, E, e , electrodes; D, D , quartz diaphragms.

will reduce the light falling on V_1 relative to V_2 , thus making the grid of V_3 more negative and producing a current in M . The response for 100% absorption is easily obtained by introducing an opaque screen in front of V_1 (and reducing the sensitivity of the amplifier). If the response of the amplifier has been determined electrically in the usual way, the instrument is then readily calibrated in terms of percentage absorption.

Two especial points need further discussion: stability of zero and sensitivity. Electrical stability presents no difficulties; after 5 or 10 min. the drift is small and steady. Most mercury arcs, however, have a tendency to flicker, and some difficulty was found in obtaining a light balance free from irregular movements. The use of the quartz reflecting plate for the balancing photo-cell helped to give stability by giving both photo-cells essentially the same view of the arc, but the most important point was choice of a suitable arc. This was specially made by the Research Laboratory of the British

Thomson Houston Co., Ltd., Rugby, and is a 125 W. high pressure lamp in a quartz tube, 1 cm. diameter \times 4 cm. long. The middle 2 cm. between the electrodes is sealed off by two quartz stabilizing diaphragms with central holes about 2 mm. diameter (see Fig. 3, D). The lamp is so mounted as to screen off all light except that from this middle section. With this arrangement the zero is stable to better than $\pm 1\%$ of full scale at maximum sensitivity. The single-stage battery-operated amplifier has proved steady and reliable in use, but some difficulty may be found in finding a valve which will function smoothly with as large a grid leak as 100 megohms.* The mains-operated amplifier is an adaptation of the cathode follower circuit described by Sowerby (1944). The necessity, for our purposes, of working off a.c. or d.c. mains has meant a rather low anode voltage on V_4 , but the response is very nearly linear over the range 0–1 mA. on M .

In Table 1 are shown the absorptions of a number of organic vapours tested with a view to their use as tracer substances. It should be noted that the light source is by no means monochromatic, although combined with the characteristics of the cadmium cell the major effect is undoubtedly due to the 2537 Å. region. Only two substances in this list appear to fulfil reasonably well the requirements (most of the rest being ruled out immediately because of their objectionable odour), namely, acetyl acetone and ethyl acetoacetate. The first of these has a slight advantage in respect of the smaller concentration needed and a slighter smell at this concentration, but it is a much less accessible compound. With these two substances 0.3 or 1.0 mg. respectively per cu.ft. evaporated from a hot plate is sufficient for reasonably accurate determinations of ventilation, and at these concentrations the smell is slight and not unpleasant. Fig. 2 shows examples of measurements made in this way (under two rather different sets of conditions).

Over the range 0–10% absorption the response of the instrument is essentially linear. Correction for Beer's law in converting from absorption to concentration is not usually necessary within this range, as the deviations from linearity do not exceed $\pm 3\%$ of the measurement, but is easily made if desired.

This apparatus is convenient in use and can easily be made self-contained; the instantaneous character of the readings allows of the following of rapidly changing phenomena such as mixing, air circulation, etc. It would also be easily adaptable for automatic recording.

* Since the above was written data have been published showing that the EF36 in triode connexion is suitable for this purpose. (See Thorp, 1945.)

(ii) *Colorimetric estimation*

The list of possible tracer substances which could be estimated colorimetrically or otherwise, after absorption in suitable solutions, is considerable, and a number of these might fulfil the requirements for ventilation measurements. We have used tertiary butyl hypochlorite and purified carbon disulphide.

The properties of tertiary butyl hypochlorite are discussed in more detail in § (iii). When absorbed into normal aqueous hydrochloric acid solution containing 0.1 % of *o*-tolidine a yellow colour is produced which can either be estimated photoelectrically or visually matched against standards prepared from potassium dichromate solution. *o*-Tolidine as commercially available is often very impure and must be thoroughly purified to give a truly colourless solution before being used for this purpose. About 0.1–0.2 mg. tertiary butyl hypochlorite per cu.ft., is a satisfactory initial con-

matching against a suitable set of standards. About 2 mg./cu.ft. of air is a suitable initial concentration for visual comparison; considerably less is necessary for photoelectric estimation.

Some methods of estimating small quantities of various substances in the air and a simple all-mains colorimeter suitable for colorimetric estimations of this type will be described elsewhere shortly.

(iii) *Estimation by test paper*

This method, while less precise than those previously described, is adequate for many purposes and requires a minimum of apparatus.

In neutral or only slightly acid solutions the reaction of hypochlorites with *o*-tolidine produces an intense blue colour. This reaction is much more sensitive than the yellow colour obtained with more acid solutions. Reproducible colours are only obtained if the acidity is accurately controlled. With

Table 1.

Substance	Tested at (c.c./1000 cu.ft.)	mg./cu.ft. for 5 % absorption in 50 cm.	log ϵ
Ethyl acetoacetate	1.2	1.1	3.2
Acetophenone	0.2	0.29	3.7
Acetyl acetone	0.6	0.29	3.6
Anethol	0.1	0.21	4.0
Cyclopentadiene	1.2	1.1	2.9
Dicyclopentadiene	1.2	1.8	2.7
Dimethylfulvene	0.1	0.25	3.7
Diphenyl	0.4	0.22	4.0
Diphenylfulvene	0.1	0.34	3.9
<i>iso</i> Eugenol	0.2	0.17	4.1
Mesityl oxide	0.2	0.25	3.7
Methyl <i>iso</i> eugenol	0.2	0.20	4.0
Phorone	0.2	0.22	3.9

centration for visual comparison; considerably less is necessary for photoelectric estimation.

At the vapour dilutions used good absorption in the sampling apparatus can be obtained at rates of air flow up to 1 cu.ft./min. by using an absorbing vessel partly filled with glass beads (Fig. 3). The efficiency of absorption can be checked by using two such units in series, but as long as this remains constant the measurement of ventilation is unaffected by the actual value. A single bubbler of this type will absorb about 80 % of the vapour from the air at a rate of 1 cu.ft./min.

Purified carbon disulphide is relatively odourless, although the smell rapidly returns on keeping, and can easily be evaporated. If absorbed into a 2 % alcoholic solution of diethylamine, a brown colour, due to the formation of copper diethyl dithiocarbamate, is formed on the addition of a drop of a 1 % alcoholic solution of cupric chloride to every 5 c.c. of the diethylamine solution. This colour may then be estimated colorimetrically or by visual

these precautions it was found that the reaction would proceed in the dry state on a filter paper and the following detailed procedure devised.

1 g. pure *o*-tolidine free-base together with 1.5 g. of benzoic acid (2.5 g.mol. of acid per g.mol. of base) are dissolved in a mixture of 60 c.c. of petroleum ether (boiling range 40–60° C.) and 40 c.c. of chloroform. This solvent was chosen as the most volatile that would dissolve the compounds; it also possesses the advantage that the blue-coloured compound produced by the action of hypochlorite is quite insoluble in it, so that the solution remains clear and colourless even though exposed at intervals to atmospheres containing considerable concentrations of hypochlorites. If kept in a stoppered brown bottle the solution is stable and only develops a slight yellow colour after a period of months. Old or impure solutions, however, in which some decomposition has taken place, result in the development of greener colours which may be difficult to match.

When making a measurement 0.1–0.2 g. of tertiary butyl hypochlorite per 1000 cu.ft. of air space are vaporized into the air of the room. This may be conveniently done, and at the same time a certain amount of mixing obtained, by pouring the measured volume of liquid on to a clean piece of fabric, such as a handkerchief or duster, and gently waving this around the room until all the liquid has evaporated. This will only take a few minutes, even in large rooms, as the ester is very volatile.

At intervals after this a single drop of the tolidinebenzoic acid solution is dropped on to a small filter paper (4 cm. diam. Whatman no. 1 is convenient), and the filter paper freely exposed to the atmosphere. A blue colour will slowly develop at a rate

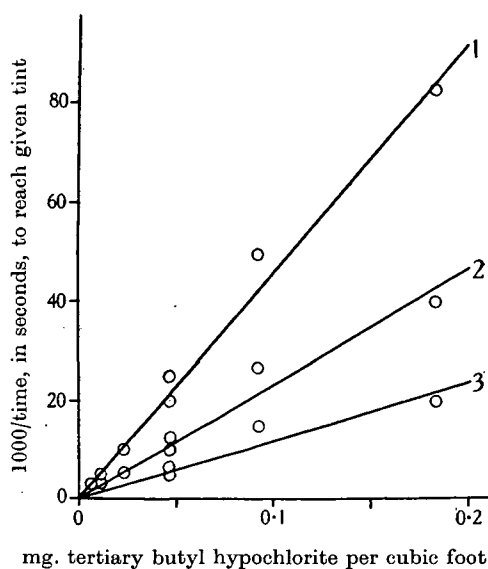


Fig. 4. Colour standards prepared from alcoholic methylene-blue solutions of the following concentrations. No. 1, 0.02 mg./c.c.; no. 2, 0.04 mg./c.c.; no. 3, 0.08 mg./c.c. The mixed unit, mg./cu.ft., is practically convenient.

depending on the concentration of hypochlorite present in the air. This concentration is estimated by measuring the time taken for the colour to match a standard colour. For exposure times below 5 min. the time taken to reach a given tint is inversely as the concentration (Fig. 4). Convenient standards may be made by dropping a drop of a solution of a suitable dye on to a similar filter paper and allowing it to dry. Methylene blue in alcoholic solution at concentrations of 0.02, 0.04 and 0.08 mg./c.c., makes a convenient series of standards, but the colour is not a true match, and while the standards are unaffected by the hypochlorite they are not entirely permanent. Methyl green is a good match for colour, but the resulting 'standards'

are not altogether unaffected by stronger concentrations of hypochlorite vapour.

It is convenient to work with more than one colour standard simultaneously, as this multiplies the number of observations. Fig. 5 shows a series of measurements made in this way in a large hospital ward. It will be seen that the precision of the method is sufficient to determine ventilation rates of this magnitude to better than $\pm 10\%$. The quantity defined above as the equivalent ventilation is by its nature often only measurable with a limited accuracy. Continuous and complete mixing of the incoming air with the air of the room can never be strictly attained, although experience suggests that such an approximation is frequently a fairly good one. In addition, the rate of ventilation is likely, especially in inhabited rooms, to be

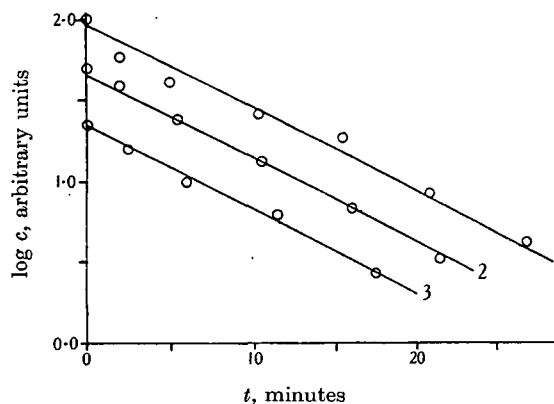


Fig. 5. 20 c.c. of a 50% solution of tertiary butyl hypochlorite in carbon tetrachloride evaporated into 45,000 cu.ft. hospital ward. Windows blacked out, but open at tops, door open and fires burning in two grates. Curves 1, 2 and 3 refer to the corresponding colour standard as in Fig. 4. Equivalent ventilation in the centre of the ward, 7.3 turn-overs/hr.

subject to continuous variation with the opening and shutting of doors and windows in the building and the varying gusts of wind outside; Fig. 2, B is of some interest in this connexion.

Tertiary butyl hypochlorite can easily be made by adding to 1 l. of 10% alkaline sodium hypochlorite solution 100 c.c. of tertiary butyl alcohol followed by sufficient acetic acid to make the solution distinctly acid, i.e. about 150 c.c. The ester separates immediately as a pale yellow liquid lighter than water and can be separated off. The operations are best done in a fume cupboard or in the open. After drying over sodium sulphate it may be diluted with an equal volume of carbon tetrachloride and used without further purification. Tertiary butyl hypochlorite is a stable substance

and will keep without decomposition for many months in a brown bottle, but is somewhat sensitive to light. The primary and secondary alkyl hypochlorites are unstable explosive substances, but even these are stated (Taylor, McMullin & Gammal, 1925) to be safe when diluted to 50 % or less with an inert solvent. Although the tertiary butyl hypochlorite is apparently quite stable, we have used it in carbon tetrachloride solution, 50 % v/v or less, as an additional safeguard.

In spite of its apparently reactive constitution, the vapour of tertiary butyl hypochlorite does not appear to react with walls or floor in a normal room and is insensitive to the presence of phenols in the air. Up to 1 g./1000 cu.ft. of phenol or mixed

creosols, 'cresylic acid', are without any detectable effect. We have, however, found the vapours from freshly painted walls to interfere seriously with the reaction, causing rapid fading of the blue colour and an apparently rapid disappearance of the hypochlorite. The presence of this interference is apparent, as the colour on the filter paper, instead of increasing in intensity continuously for at least 5 min., reaches a maximum after even as short a time as 1 min. and then fades again.

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