

# A Review of Experimental Techniques for the Investigation of Natural Ventilation in Buildings

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## I. INTRODUCTION

### I:1. General introduction

VENTILATION is necessary in buildings in order to maintain low odour levels and to remove carbon dioxide and replace oxygen. An unfortunate additional effect is that, in a heated building, heat is lost with the foul air.

Odour removal techniques are available and may in some cases be economical, but in many building types in this country, it is the case and will continue to be the case, that heat loss is intimately tied to odour removal.

Satisfactory ventilation rates can often be achieved by a 'natural' system in which the pressure differential due to wind or the stack effect (or a combination of both) is used to drive the air, and some control is provided by manual setting of openings (e.g. windows). The use of a natural ventilation system means that the ventilation rate and hence a substantial proportion of the heat loss from the building, is as much at the mercy of the user and the local weather conditions as it is under the control of the designer. This, in turn, means that a satisfactory knowledge of ventilation rates as they are found to occur in buildings in use is necessary both for adequate thermal assessment of existing buildings and for the thermal design of new buildings.

As a preliminary in an assessment of the thermal performance of the 'solar heated' St. George's School, Wallasey[1], this Unit has surveyed available techniques of ventilation measurement and this paper is a summary of the survey.

*The measurement of natural ventilation of buildings*—Although there are a number of papers describing techniques and results of experiments on the measurement of natural ventilation, no comprehensive survey has been published. This paper is concerned with techniques, but since the suitability of a technique depends to some extent on the quantity it is to determine, some results are also mentioned.

There are three principal sections: *Tracer techniques* are dealt with at some length because of their widespread use and obvious advantages; *measurement of low airspeeds* is a large subject and the second section is restricted to short descriptions of the various types of (non-tracer) instruments; *the use of models* is a well-established practice in many fields of fluid flow and this section attempts to state the basic requirements and to describe the limitations of the method as it has been applied to natural ventilation investigations.

### I:2. The concept of a ventilation rate

The concept of a *ventilation rate*, as so many room air changes per hour, is somewhat misleading, especially where natural ventilation is concerned. It is not without its uses as a crude indication of the 'fresh' air flow into a room or building but it is,

unfortunately, easily open to misinterpretation and misuse.

The mixing of incoming air with the air already in a room (or building) falls in practice between the two extremes of perfect (i.e. instantaneous, homogeneous) mixing and no mixing (which may imply no air change if the fresh air by-passes the old, or complete changes if the new drives the old before it). Thus the 'air change rate' usually quoted (i.e. the incoming air per hour expressed in terms of the volume of the room) does not correspond to the number of times per hour that the room air is changed. This would only be so if the incoming air drove the 'old' air out before it, which is not generally speaking a good approximation to the airflow in naturally ventilated buildings. In fact, it has been noted[2] that if the mixing is 'perfect', one air change changes about 63 per cent of the room air.

If the mixing is not homogeneous (which is almost certain to be the case with whole-building studies especially with closed internal doors) the ventilation rate of one region will not be the same as at all other regions and an overall rate is useful only for a limited range of applications (it may be useful for determining the total heat load required, for example, but useless for showing how the heating should be distributed through a building). There is also a tendency to assume that a given air change rate is of the same thermal importance in spaces of different shapes and sizes. But when, for example, heat flow from the surfaces of the enclosure is important, this is not so. It is possible, indeed almost certain if the whole range of possible wind directions is taken into account, that in studies of a room or group of rooms, some of the incoming air will have come from some other part of the building and thus have different thermal and hygienic properties from air from the outside. In this case, the apparent ventilation rate is misleading as is any calculated rate which does not take into account this influx.

A more realistic measure is the *transfer index* between two points as described by Lidwell[3]. This is a measure of the movement of air between two points. It would obviously be impossible to determine this index for all possible pairs of points but it is possible to determine the general flow pattern qualitatively and then to measure the most important transfer indices quantitatively. In practice, of course, measurement techniques demand that indices must be measured between two regions, albeit small, and not between points. The size of these regions can be chosen with regard to the detail required for any particular application. In particular, transfer indices may be determined between rooms or between a room and the outside, and this has been done implicitly whenever corrections have been made for recirculation[4-6]. These transfer indices between large regions are the components of the apparent ventilation rate and in most instances knowledge of these components is more

important than the crude rate itself. Small-region transfer indices have been used in the study of infection in hospital wards[7] and operating theatres, and could be applied to the study of the homogeneity or otherwise of ventilation.

Both ventilation rates and transfer indices change with conditions of usage and meteorological conditions. While the variations of ventilation rate with meteorological conditions are widely appreciated and several workers have noted this quantitatively or qualitatively for particular buildings or parts of buildings[4-6, 8-18] very few observations of ventilation under conditions of normal usage have been published[4, 13].

It would seem likely that the intra-building air-flow and hence the transfer indices could vary considerably with variations of either of these groups of conditions and that not only would the apparent ventilation rate change, but also the relative importance of its components. Thus, while it has not been established that the apparent ventilation rate is misleading in these circumstances, the possibility cannot be ruled out unless the transfer indices are known to be unaffected to any appreciable extent by changes in meteorological conditions or the conditions of usage (the latter may be influenced by the former—control of windows is obviously partially weather-dependent, while air movement from room to room, for example, is much less so).

## II. TRACER GAS TECHNIQUES

### II:1. Introduction

The use of tracer gases to measure ventilation rates is well known and has been practised on many occasions. Indeed, it is very difficult to see what alternative method could rival it for ease of producing readings in the field. For these reasons, this section is of some length and more detailed than the sections on other methods. The list of references is believed to be fairly comprehensive and although most of them are in English, their origins are widespread.

The section is subdivided into the following subsections:

II:2.—A summary of the various methods that have been proposed for inferring features of the ventilation from observations of tracer gases: namely the methods of rate of decay; equilibrium concentration; transfer index; steady concentration. The more important advantages and disadvantages are given.

II:3.—Since several of these methods imply assumptions about the mixing of air in rooms, this section describes the processes involved, and the results of their action, as far as can be deduced from the observations made by various authors.

II:4.—A brief summary of other types of processes which may complicate the use of tracers.

II:5.—A short account of the types of experimental error which are likely to occur when the various methods are used.

II:6.—Descriptions of the more commonly used concentration measuring techniques and of some other methods that have been used or suggested.

II:7.—In tabular form, estimates of accuracies and comparisons of different methods extracted from the literature.

II:8.—A comparison of tracer gases for use in occupied areas, including crude cost estimates.

II:9.—A summary of references.

The need for the presence of an experimenter (or experimenters) in the place of investigation or of a good deal of plumbing to introduce tracer and extract samples has led some people[12, 18] to make a series of tests to obtain a correlation between ventilation and some more easily recorded quality, such as window opening. This clearly has advantages, especially for continuous recording, in occupied rooms, but on the other hand may not always be reliable due to imperfect correlation.

### II:2. Tracer methods

II:2(a). *Rate of decay method*—In this method, a quantity of tracer is released either at a number of points in a room or at one point near a low speed fan. The purpose of the fan or the numerous release points is to produce a uniform (or near-uniform) concentration throughout the room. The concentration decay is then exponential (assuming perfect mixing—see for example [16] or [19]) and by sampling the air at several times the apparent ventilation rate can be determined.

Since mixing is never perfect (as is shown by the need to mix the tracer artificially) measurements made at one point in a room may not be reliable. In practice, one of three techniques is used to offset this:

- (i) Air is sampled at several points, mixed and the combined concentration used to determine the decay rate.
- (ii) Decay rates are found at several points in a 'trial run' and the position giving a rate nearest the mean is used for further measurements. Sometimes the mean rate at the three 'best' positions is used.
- (iii) Decay rates are found at several points, and their mean determined.

If the mean rate is required, (ii) and (iii) are estimates of it, with (iii) having the better reliability. The estimate given by (i) is subject to a time-dependent bias error. As time goes on, this estimate tends to the slowest rate of the various sampling positions.

With imperfect mixing, different parts of a room will lose tracer at different rates. In these conditions, if there is a transfer of tracer between two such regions, the apparent ventilation rate of the region receiving tracer tends to the lower of the two rates. Extension of this model leads one to suppose that estimates of the mean rate are likely to be underestimates.

**Advantages**

(1) The method and the analysis of results are relatively simple and the period over which measurements have to be taken is not unduly long.

**Disadvantages**

(1) Doubt about the accuracy of the measured rate or average rate (systematic errors).

(2) Sometimes (for example, when there is a relatively large flow into enclosed spaces such as furniture) the decay of tracer is non-exponential. In this case, the fitting of an exponential decay curve to the data is difficult.

(3) To obtain uniform concentration at the start of a test requires either complicated pipework and many release points, or artificially stirring the air, which may alter the prevailing conditions.

II:2(b). *Equilibrium concentration method*—If the tracer is emitted continuously at a uniform rate, the concentration at any point in the room will approach an equilibrium value if conditions are steady. With perfect mixing, this equilibrium would be the same at all points. Knowing the emission rate of tracer and the equilibrium concentration, the ventilation rate can easily be calculated. If the mixing is not perfect, the concentration will vary from point to point and under these conditions, the concentration is proportional to the transfer index (see II:2(c)) from the point of emission to the measuring points, for any given rate of emission.

**Advantages**

(1) A straightforward single measurement is sufficient if perfect mixing occurs.

(2) The transfer index from the tracer release point to any point in the room can be measured, and only one detector is needed.

**Disadvantages**

(1) A long time (of the order of several hours) is usually needed before equilibrium is approached. As a result of this, more tracer is needed per test than the other methods.

(2) Errors due to non-static conditions of weather and room usage are more likely to occur and difficulties may arise in ensuring a constant rate of gas emission.

II:2(c). *The transfer index technique*—The 'transfer index' between two points or 'index of exposure to contamination', as it is called in studies of infection, was proposed as a measure of ventilation by O. M. Lidwell in 1960. Basically, the technique is to determine the time integral of tracer concentration at one point following the liberation of unit volume of tracer at another. The index thus found is a function of the position of both points but does not depend on any assumptions of perfect mixing. (Note that the value of the index from A to B will not, in general, be the same as the index from B to A and that it is possible for the index to be greater than unity when mixing is not perfect.)

The reciprocal of the transfer index has the dimensions of a ventilation rate and Lidwell calls it the 'effective ventilation'. If perfect mixing occurs, the effective ventilation is the rate of supply of fresh air that would be deduced either from the rate of decay of the tracer or from its equilibrium concen-

tration. In the latter case, even without perfect mixing, the equilibrium concentration at a point, divided by the rate of emission of tracer is the same as the transfer index from the point of emission to the point of measurement.

The procedure adopted is to release a known volume of gas at one point and to sample the concentration at several other points. It is necessary to know the concentration of tracer existing before the start of the test (which may be a naturally occurring concentration, or tracer remaining from a previous test).

In principle, the concentration integral can be measured directly by an accumulative detector from a sample drawn continuously at a uniform rate throughout the test (bearing in mind that the actual removal of tracer by the measuring apparatus must be insignificant). This technique has been used, but has the practical drawback that since the concentration eventually declines slowly to the background level, a long sampling time is required to reduce cut-off errors.

Lidwell shortened the measurement time by recording the tracer concentration continuously and applying a cut-off correction based on the assumption that the final decay is exponential. In fact, this exponential decay is the quantity measured in the rate-of-decay technique.

In particular cases, it may be possible to draw inferences about the circulation and recirculation of air from particular concentration/time plots (for example, a series of peaks indicating that the same sample of tracer is recirculating, will enable the circulation time to be found, and the relative broadening of the peaks is an indication of the mixing present).

**Advantages**

(1) The derived quantity is meaningful without the need to make hypotheses about mixing.

**Disadvantages**

(1) Many measurement positions are needed to determine the ventilation in one room (but this is reflected in the extra information gained).

(2) Either a long time interval or frequent (or continuous) determinations of concentrations are required.

II:2(d). *Steady concentration method*—This is really a variation of the equilibrium concentration and transfer index methods although it predates the latter in the literature. Tracer is injected at one point and the concentration at some other point is measured. The tracer injection is controlled so as to give a steady, known concentration at the measurement point. Ideally this is done automatically. Then, if the concentration at the detection point and the mean rate of the tracer injection when the concentration is static are known, the transfer index can be calculated. If perfect mixing is assumed, the ventilation rate can also be evaluated. Apparently, the only attempts to use the method have used water vapour, which is by no means an ideal tracer.

**Advantages**

- (1) No mixing hypothesis is invoked.
- (2) The equilibrium concentration can be predetermined and is reached more rapidly than in the equilibrium concentration method.
- (3) When the steady state is achieved, the methods of the equilibrium concentration technique may be applied.

**Disadvantages**

- (1) More complicated apparatus for gas release will be needed than for other methods.
- (2) Only one transfer index can be evaluated at a time—(see advantage 3 for ways of overcoming this at the expense of more equipment).
- (3) There is almost certain to be a lag between tracer injection and change of concentration at the detector and this can introduce error and oppose the attainment of a steady concentration.

**II:3. *Mixing processes in a room***

The assumption of perfect mixing of incoming air with air already in a room is often made in ventilation rate estimations. The majority of workers who have used tracer techniques to estimate ventilation rates have concerned themselves with 'average' rates estimated from the mean decay rate in various parts of a room. For this technique to be possible, it is necessary to be able to produce a near-uniform tracer concentration throughout the room initially. If this is not so, the movement of tracer within the room will affect the estimate. Since the accuracy to which this assumption holds underpins the validity of the concept of a single ventilation rate and its estimation, it is of fundamental importance to have reliable estimates of its truth or otherwise. Knowledge of the relative importance of the various possible influences would enable the desired properties of a tracer gas to be more confidently predicted. Unfortunately, no comprehensive study of intra-room mixing appears to have been published. The following account is therefore largely based on circumstantial evidence from observations made by various people in the course of their studies, for it would be untrue to say that these investigators had dismissed the question out of hand.

**II:3(a). *Comparison of the processes which may be important***—Molecular diffusion is too slow a process to be directly responsible for any appreciable part of mixing on a whole-room scale. It has been calculated[20] that the most rapidly diffusing gas, hydrogen, requires over an hour to reach 95 per cent of its final concentration (in air) at a point  $7\frac{1}{2}$  ft above a layer of gas. (However, a point  $7\frac{1}{2}$  in. from the source would attain 95 per cent of its final concentration in about  $\frac{1}{2}$  min.) When compared with observed times of 20 min or less for tracer concentration to become 'acceptably uniform' throughout a room, it is apparent that there must be other processes, at least three times faster at work.

In almost calm, thermally stable atmospheric conditions, eddy diffusivities greater than the molecular diffusivities by factors of about  $10^3$  have been observed[16]. However, even in Beaufort 1 winds (which are almost calm by atmospheric standards) the air speeds are an order of magnitude greater than air speeds in naturally ventilated rooms. Differences of velocity of this order are likely to reduce the eddy diffusivity appreciably. That diffusion is present to a significant extent is demonstrated by the relatively good mixing of small quantities of tracer with air. For example, if hydrogen, released into air remained as a 'bubble' of high concentration, the potential energy due to its density difference from the air would be much larger than the kinetic energy of convection currents and stratification would take place. Only at low concentrations can this be overcome and the fact that observed vertical concentration gradients in the absence of artificial mixing are small, shows that while the tendency for stratification is present, mixing is sufficient to reduce it greatly.

Thermally induced currents in excess of 20 ft/min have been measured[2] in rooms in the absence of any measurable ventilation rate. At the same time air speeds in other parts of the room were as low as 3 ft/min. Other workers[6] observed that about 6 min was sufficient time for uniform mixing in similar circumstances. This gives 18 ft and over 120 ft respectively as the extreme values of path lengths of gas. Such path lengths tens of feet long are clearly large enough to carry out the distribution of the tracer, and the question which next arises is whether the currents circulate throughout the whole room. The airflow patterns noted by these workers show a marked tendency for a relatively rapid circulation around the surfaces of the room, and generally slow 'eddying' of air movements elsewhere. Van Straaten[21] thinks a 3 in. boundary layer likely at low air change rates (from observations of the temperature gradient near walls[22]). Lidwell[7] observed a circulation time of about 4 min in a room and noted that acetone needed about five times this to attain a fairly uniform concentration.

At normal ventilation rates, this pattern still seems to be basically true, although the upper limit of possible airspeed is increased and additional flows and counter-flows across the room may be introduced. 'High-speed' draughts and 'through ventilation' at high ventilation rates have been noted to upset the near uniformity of conditions and so presumably change the airflow pattern significantly.

These observations suggest that a circulation of air currents around a room, due to convection or other causes, is the principal transport mechanism, with eddy or molecular diffusion (or both) providing smaller scale mixing.

II:3(b). *Experimental observations of the uniformity of mixing*—Willax and Maier-Leibnitz[23] defined an airchange factor  $b$  as

$$b = \frac{\int_{t_1}^{t_2} C \cdot dt}{\int_{t_1}^{t_2} \bar{C} \cdot dt} \quad \text{where}$$

$C$  is the actual concentration of a tracer  
and  
 $\bar{C}$  is the concentration for perfect mixing.

They introduced a radio-active tracer into the inlet air of a test room and observed values of  $b$  from about 0.90 to 1.25.

Unfortunately, the effective air change rate is not easily deduced from the factor (and the value of the factor usually changes with time even with steady air change, because mixing is imperfect). Over long time intervals or when the interval covers most of the build-up and decay of concentration, the factor becomes close to the ratio of the actual transfer index (from air inlet to measuring site) to the index

which would result from perfect mixing. It is also, in these conditions, the ratio of the ventilation rate with perfect mixing, to the effective ventilation observed. That is to say, the factor is an indicator of the effectiveness with which old air is replaced by new.

Table 1 shows the variations of apparent ventilation rate observed by various investigators in different parts of rooms. Although part of these differences can undoubtedly be blamed on experimental errors, the data given by Roux and Van Straaten[22] shows that there are also systematic variations from place to place. In one series of 19 tests, using three points in the same room, the apparent ventilation rate at one site was never less than the mean, while at the other two sites it was never greater than the mean value. In another, similar series of 14 tests there was an average (algebraic) difference between two sites of 5 per cent of the mean rate.

Table 1. Observed variations of apparent ventilation rate with position in a room, by the rate of decay method

Gas and measurement technique	Mean rate (ch/h)	Maximum observed variation from mean (%)	Observer
<i>(i) Tracer not mixed</i>			
H <sub>2</sub> katharometer	7.15	13	Marley[24]
H <sub>2</sub> katharometer	6.62	4	Van Straaten[21]
H <sub>2</sub> katharometer	3.86	3	Van Straaten[21]
H <sub>2</sub> katharometer	2.12	14	Van Straaten[21]
<i>(ii) Tracer mixed in initially</i>			
H <sub>2</sub> katharometer	7.25	3	Marley[24]
H <sub>2</sub> katharometer	7.75	3	Marley[24]
H <sub>2</sub> katharometer	0.5-8.0	0	Van Straaten[21]
CO <sub>2</sub> chemical analysis	0.53	13	Renbourn <i>et al.</i> [16]
CO <sub>2</sub> chemical analysis	1.37	4	Renbourn <i>et al.</i> [16]
CO <sub>2</sub> chemical analysis	3.30	2	Renbourn <i>et al.</i> [16]
CO <sub>2</sub> chemical analysis	3.42	3	Renbourn <i>et al.</i> [16]
CO <sub>2</sub> chemical analysis	4.88	2	Renbourn <i>et al.</i> [16]
CO <sub>2</sub> chemical analysis	7.15	7	Renbourn <i>et al.</i> [16]
CO Infra-red absorption	0.52	6	Oppl and Vasak[25]
<i>(iii) Tracer distributed throughout room without fan mixing</i>			
H <sub>2</sub> katharometer	0.7	0 (<7)	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	0.8	12	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	0.9	11*	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	1.0	10*	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	1.1	27*	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	1.2	8*	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	1.3	0 (<4)	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	1.4	0 (<4)	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	1.5	6*	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	1.6	6*	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	1.8	5*	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	2.3	0 (<3)	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	2.5	8	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	2.6	0 (<2)	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	2.9	0 (<2)	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	3.3	6	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	4.3	0 (<2)	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	4.9	0 (<1)	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	5.5	0 (<1)	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	7.1	1*	Roux and Van Straaten[22]
H <sub>2</sub> katharometer	9.8	0 (<0.1)	Roux and Van Straaten[22]

\* Worst case of a number of tests.

N.B. These variations may be due to imperfect mixing or measurement errors.

#### II:4. Non-instrumental difficulties

II:4(a). *Rate of decay method*—Apart from problems of a non-uniform rate, other non-instrumental difficulties can arise. These fall into the following categories:

- (i) Loss of tracer other than by ventilation.
  - (ii) Removal of tracer at a different rate to that of air (but by the same process)
  - (iii) Uncontrolled production of tracer
  - (iv) Recirculation of air and tracer via cupboards and adjoining rooms.
- (i), (ii) and (iii) change the amount of tracer present and may alter the shape of the decay curve. (iv) usually has the effect of making the decay non-exponential and thus making the rate difficult to determine.

- (i) Loss of tracer other than by ventilation.

This can occur in a number of ways:

(a) *Condensation*: if the tracer used is a vapour, it is possible for the air to become saturated and for condensation to take place. This may occur on cold surfaces even when the rest of the room air is below saturation. The condensed tracer may then be lost or, more probably, will evaporate again when either the vapour pressure falls or it drips on to a warmer surface.

(b) *Chemical reaction*: a tracer may react with some of the substances present in the air or on the surface. An example is reaction with paintwork, especially when the latter is fresh, or combustion, if flames are present. These losses are usually permanent and may be continuous for an indefinite length of time or may decrease as the reagent supplies are exhausted.

(c) *Solution*: if water is present in a room, the tracer may dissolve, if only partially. Most tracer substances which have been used are not very soluble in water. Unless the water is running, the process will die away as equilibrium is reached, but a change of temperature may release or dissolve more gas.

(d) *Settling and filtering*: particulate tracers and aerosols may be removed by processes which would not affect gases or vapours. Both settling out and removal by any filters which may be present (even with natural ventilation there may be filtering agencies present) will mainly affect the larger particles. Particles which have settled out may reappear in the air again.

- (ii) Removal of air and tracer at different rates by the same process.

This can occur because of:

(a) *Concentration variations*: if the concentration of the tracer near outflows of air is different from the mean concentration, the rate of loss of tracer will not be the same as the rate of loss of air. Unless perfect mixing is taking place, there is bound to be some error of this type, even when the initial concentration is uniform and stratification is absent.

(b) *Diffusion*: in principle the diffusion of air or tracer through openings or porous walls to the atmosphere should separate the gases. In practice, these effects are usually swamped by other processes of mass transfer and no appreciable error results. Howard[14] has, however, noted errors assumed due to diffusion, in rooms with weatherboard walls.

- (iii) Uncontrolled production of tracer.

Occasionally a tracer is used which is produced within the experimental area. Typical cases are the use of CO<sub>2</sub> or water vapour in occupied rooms. If the emission is constant, the decay rate is unaffected and it is variations in the rate of production which are normally important. Similar errors are caused if the concentration of the tracer gas in the incoming air alters.

- (iv) Recirculation of air and tracer.

It often happens that it is possible for 'labelled' air removed from the experimental region to return, possibly at a lower tracer concentration, after a period of time. Unless the decrease of tracer has been the same as in the experimental region in this time, the returning air will cause a deviation from an exponential decay rate. This recirculation may be desirable in that it is an indication of the 'stale' air which re-enters the room but this advantage is largely offset by the difficulty in estimating a ventilation rate from a non-exponential decay. Examples of causes of this error are flow into adjoining rooms and back, and flow into and out of furniture such as cupboards and desks.

II:4(b). *Equilibrium concentration method*—All the errors caused by (i), (ii) and (iii) may still be important, although the actual size of these errors is not the same. In particular, a constant source of tracer will affect the equilibrium concentration but not the exponential decay towards it. Constant background may, of course, be calibrated out. Errors due to (iv) diminish as equilibrium is approached. The quality determined by this method is (assuming perfect mixing) the rate of exchange of 'labelled' air with unlabelled from all sources.

II:4(c). *Transfer index method*—This is subject to errors of types (i), (ii) and (iii) in much the same way as the equilibrium concentration method. Recirculation errors may occur but not in quite the same way as in the rate-of-decay method. Recirculation of tracer within the room will not affect the accuracy of the index (although since it implies imperfect mixing, the 'effective ventilation' will be decreased).

II:4(d). *Steady concentration method*—The errors are the same as in the transfer index method.

#### II:5. Accumulation of measurement errors

II:5(a). *Rate of decay method*—Errors in the measurement of both time and concentration are important. For small errors, the proportional error in ventilation rate estimate is linearly dependent on the proportional errors in the time and concentration estimates. Since the estimated

rate is proportional to the logarithm of the concentration at any time, there is a bias introduced by the errors within the logarithmic term. Thus, averaging of readings cannot be guaranteed to produce an unbiased estimate of the rate. Since differences of time and the logarithm of concentration are used, the errors may be quite large in comparison to the differences, although small compared to the absolute values.

The following example shows the extremes possible under fairly representative conditions, which are roughly what one might expect using a katharometer and stop watch.

True ventilation rate = 3.0 changes/h  
 Initial concentration = 1 per cent  
 Samples taken at 10 and 15 min after release  
 Accuracies: concentration  $\pm 0.01$  per cent of tracer; time  $\pm \frac{1}{2}$  s.

Maximum possible estimate of  $\dot{R}$ :  
 $\dot{R}_{\max} = 3.40$  ch/h  
 Minimum possible estimate of  $\dot{R}$ :  
 $\dot{R}_{\min} = 2.53$  ch/h  
 So there is a range of 0.87 ch/h possible experimental error.

} Resulting  
 from the  
 errors noted.

Averaging the extremes;  $\dot{R}_{\text{mean}} = 2.97$  ch/h, that is a bias of 0.03 ch/h has been introduced. (Unbiased errors would average to the true rate.) In practice, the use of a series of readings would reduce the uncertainty somewhat, as an error tending to cause an underestimation of the rate will increase the next (or immediately preceding) estimate and vice versa. The bias error will remain, and be an underestimate of the true rate.

II:5(b). *Equilibrium concentration method*—The accuracies of measurement of tracer concentration and of tracer release are the critical factors. If each can be measured to  $\pm 1$  per cent, the rate can be estimated to  $\pm 2$  per cent. In the example used above, this corresponds to  $3.00 \pm 0.03$  ch/h. There is, however, a bias error due to the finite length of time which elapses between the start of tracer release and measurement. At a ventilation rate of 3 ch/h, this error is about 5 per cent after 1 h and 2.5 per cent after 2 h. It is always an overestimate of the true rate. An iterative correction of the bias can easily be made, provided that sufficient time has elapsed for the error to be only a few percent. In practice, this means several hours for normally ventilated rooms.

II:5(c). *Transfer index method*—This method subdivides into three different variations:

(i) Continuous measurement of concentration.

The total time of measurement and the integrated concentration are required. Random errors of the concentration measurement should be small since they are integrated, and as a fairly long time period is likely, the proportional error in this should also be small. Random errors should thus be less in the equilibrium concentration method. A truncation error due to the finite measuring interval will occur.

At a ventilation rate of 3 changes per hour, this is  $\sim 37$  per cent with an interval of 20 min and  $\sim 5$  per cent with 1 hour. A correction factor can be applied, assuming the decay after truncation to be exponential. This correction is subject to the errors of the rate of decay method, that is, to greater measurement errors and some bias. It is, therefore, desirable for the correction to be fairly small, if the advantages of analysis of the method are required.

(ii) Discontinuous measurement.

The integration has to be performed numerically and, in addition to random measurement errors of concentration there are errors of the time of measurement. The effect of these is to cause additional errors in the concentration estimation which are proportional to the rate of change of concentration. With exponential decay curves, this means that these extra errors are proportional to the apparent ventilation rate. To some extent, these random errors will be decreased by the process of integration, the actual decrease varying with the form of numerical integration used. The comments on truncation error made for the continuous measurement variation apply equally to discontinuous measurements.

(iii) Continuous rate sampling.

If sampling is carried out at a steady rate and one combined sample obtained, the only measurements that can be carried out are of the average tracer concentration and the total sampling time. As no correction for truncation error can be made, a long time interval is necessary and thus the proportional error of the time estimation should be low. The concentration can usually be determined several times for the same sample and random errors of measurement therefore reduced. These also apply to cumulative detection of tracer except that repeated estimations of the final result may not always be possible.

II:5(d). *Steady concentration method*—The relevant factors are the mean rate of tracer release and the concentration. The rate of tracer release is a simple volume or weight change per unit time and the random errors are straightforward. The accuracy to which the concentration is known is less simple, since in addition to the normal measurement errors, the concentration may oscillate about its mean value in an asymmetric manner. The limits of these excursions will be dependent on the manner of release of tracer, the lag between release and detection points and the sensitivity of the detector.

## II:6. Concentration measuring instruments

In all the techniques of deducing ventilation rate, accuracy and convenience of use of the measuring instruments are important. Automatic analysis, giving immediate estimations is an advantage with all techniques but is well nigh indispensable when using the steady concentration method.

The rate of decay method involves the calculation of ratios of concentrations and so for this method, the ratio of the extremes of concentration measurable is more significant than their difference. The upper limit may be set by the instrument or by the properties of the tracer but the lower limit is usually set by the accuracy of measurement. The most common measurement devices are described below:

II:6(a). *Katharometers*—Bahfleth *et al.*[9]; Coblenz and Achenbach[26]; Daynes[27]; and Van Straaten[21]. The katharometer measures changes in the thermal conductivity of the air/tracer mixture. The instrument is essentially a Wheatstone bridge circuit, whose arms are platinum filaments or thermistors in small gas-filled cells. Two of the cells are filled with a reference gas and the other two are open to the sample being examined. A current through the bridge raises the filament temperature by about 15 deg C, the exact temperature and thus the resistance depending on the heat loss rate in the cell. Radiation losses are kept low by the small size of the temperature difference between filament and cell and convection losses are reduced by the small size of the cells. The out-of-balance current is calibrated against concentration. The calibration is not normally linear over a wide range of concentrations, although usually assumed so over the limited ranges used. Indeed, some possible tracers, such as water vapour, can give ambiguous readings.

Apart from any lags in the sampling line, there is a 'dead time' in the instrument and the reading is then approached exponentially. In one commercial instrument, using hydrogen as the tracer, the 'dead time' is  $4\frac{1}{2}$  s and the exponent factor is about  $0.13\text{ s}^{-1}$  (i.e. a time constant of about 8 s). Thus, about half a minute is required before a good estimation of the true concentration is made. For continuous observations of the concentration, this time is reduced by the absence of the dead time. Since sudden changes of concentration are unlikely, the instrument response time is also less important. Other katharometers and other tracers are likely, to be slower in response, and have greater dead periods (with  $\text{CO}_2$  the same type of katharometer has dead period and time constants approximately twice as long as for  $\text{H}_2$ ).

As all changes of air composition will affect the thermal conductivity of the mixture, gases and vapours which are present but whose concentration may vary (such as  $\text{CO}_2$  and water vapour) must be removed from the samples. This is normally accomplished by drawing the gas into the katharometer through one or more absorption chambers. If they are present in large and varying amounts, there will still be errors, caused by the removal of part of the mixture. The principal source of error is due to drift of the zero for various reasons. To minimize this, Van Straaten[21] has suggested that the zero should be checked before and after each measurement. Temperature effects can be reduced by having the instrument in a constant temperature

enclosure, but pressure effects are also present (which, incidentally, shows that some convection does occur in the cells—conduction being largely independent of pressure changes).

A thermistor katharometer was tested at the National Bureau of Standards in the U.S.A. by Coblenz and Achenbach[26] and their recommendations included these:

- (i) Air should be drawn through the cells for at least an hour before any measurements are taken.
- (ii) The rate of gas flow to the instrument should be kept constant.
- (iii) The shortest possible sampling lines should be used (and lags between sampling and measurement taken into account).
- (iv) Numerous readings should be taken to average out drift and parallax errors.

With these precautions and a range of helium concentrations of 0.4–1.4 per cent the instrument was judged satisfactory for infiltration measurements

*Uséable range.*

Widest practicable range of concentrations: 0.4–1.2 per cent (He).

(N.B. The upper limit of He is determined by an arbitrary stipulation that the density of the mixture shall not vary from that of the air by more than 1 per cent. The lower limit is set by Coblenz's recommendations—the lowest detectable is less than one tenth of this.)

Maximum ratio of concentration extremes 3.0 : 1 ( $\text{H}_2$  or He).

If a unit of wider range than the one tested by Coblenz (or several units calibrated for different ranges) is available then a range of concentrations of 0.3–1.1 per cent is possible using hydrogen, i.e. a ratio of 3.7 : 1.

Although other gases may be used at higher concentrations, their thermal conductivities are closer to that of air and the minimum concentration detectable by katharometers is also high.

II:6(b). *Chemical analysis*—Lidwell *et al.*[7],[19]; Renbourn *et al.*[16]. One desirable property of any tracer is that it should not be very reactive chemically with materials in a room, at room temperature. Despite this, there are a number of tracer gases which have been used which can be detected chemically. There are two possible reasons for using these methods, greater accuracy or greater convenience. Qualitative analysis of low concentrations of  $\text{CO}_2$  is about as accurate as the katharometer method, according to Renbourn[16] but is much less convenient. On the other hand, Lidwell and others[7],[19] have used various organic vapours as tracers and measured the concentration colorimetrically or by pH changes. Visual colour matching is perhaps rather inconvenient but photoelectric methods are more sensitive and reproducible. Lidwell's apparatus for measuring transfer indices using acetone and pH changes was quite

simple but the reliability of the estimates was poor. Due to the fact that the relationship between pH and concentration is approximately logarithmic, random measurement errors will produce a biased estimate of the transfer index (although the bias will probably be small compared to the uncertainty of the estimate). The widest practical range of concentrations is not known but acetone, for example, can be detected above concentrations of 0.01 per cent. For reasonable accuracy it is obviously advisable to keep well above this and a useable range of 0.1–1 per cent is more realistic.

II:6(c). *Infra-red absorption*—Most heteroatomic gases have absorption lines in the infra-red part of the spectrum. By determining the transmission of radiation at an absorption frequency, through a fixed path length, the concentration of one gas in another can be determined. In practice, the transmission is compared with that of a reference gas. This principle of measurement can be applied from very low concentrations (hundreds of parts per million and even lower) up to quite high ones (50 per cent or more) for many gases, and in practice quite large changes of range can be accommodated in one instrument.

The method is well suited to continuous measurements, as the output is continuous and electrical in form. A response time of about 15 s in some commercial apparatus (to final concentration) will cause some lag, which may be important if rapid changes of concentration occur. For this situation there is at least one unit with an appreciably faster response.

Daily checking of the calibration (if in constant use) is advised by the manufacturers of this apparatus.

*Useable range.* Widest practicable range of concentrations: 0.0001–2 per cent ( $N_2O$  or  $CO_2$ ).

(Upper limit is arbitrary 1 per cent density difference of air to air-tracer mixture.)

Maximum ratio of concentration extremes;  $\sim 2000 : 1$ .

If conditions allow the use of CO the useable range is much greater due to its smaller density difference from air.

II:6(d). *Radio-active tracers*—Collins and Smith[28]; Howland *et al.*[6]. Of the three ejected products of radio-active decay, namely  $\alpha$ - and  $\beta$ -particles and  $\gamma$  radiation, only  $\beta$  particles have been used to measure tracer concentrations. Both types of particles travel, on average, a matter of inches through air (from materials that can be used as tracers) but  $\gamma$  radiation has a much longer range. In principle, it would be possible to count the total radiation in a room with one detector, provided that there is no heavy material such as machinery in the room.

Radio-active tracers can be detected at very low concentrations. There is, though, a certain randomness in radio-active decay and a count of  $N$   $\beta$ -particles is subject to a standard error of  $\pm N^{\frac{1}{2}}$ , that

is, a proportionate error of  $\pm (1/N^{\frac{1}{2}})$ . Thus, to reduce the error  $N$  must be increased. This can be done either by increasing the tracer concentration or increasing the sampling time.

Measurements of either  $\alpha$ ,  $\beta$  or  $\gamma$  activity may be made with geiger counters or scintillation detectors.

Although there is normally no actual withdrawal of a sample (the counter receives particles from a surrounding volume of several inches radius) sampling errors do occur. Since the sampling interval is of finite length, there is an error in the determination of the tracer concentration. If the decay is exponential, the bias error introduced by the 'averaging' of the reading to the centre of the sampling interval is  $2(\sinh TR)/R$  (where  $R$  is the apparent ventilation rate and  $T$  is the sampling interval). In practice, this would be of the order of 1 per cent. If  $R$ ,  $T$  are constant and the decay truly exponential, this bias vanishes in estimations of the rate of decay. Integration methods, such as transfer index determinations are not subject to the error as the time integral of concentration is determined directly.

Other errors which are peculiar to the use of radio-active tracers (although not really connected with the detection) are background radiation and radio-active decay of tracer. The former can be determined for a particular site and instrument and typically might be about 100 counts/min. The radio-active decay of the tracer will cause an error in the apparent ventilation rate which can be corrected for, and will hasten the reduction of the activity to the threshold for the instrument. Argon-41 is rather poor in this respect as it has a half-life of only 110 min. Krypton-85 is much more stable, having a half-life of 9.4 years.

Typical range of concentrations possible: (1.7–6.7)  $\times 10^{-10}$  per cent (krypton).

Ratio of extreme concentrations possible 2.5 : 1. The maximum concentration of  $^{85}Kr$  or  $^{133}Xe$  that is permitted in occupied areas is  $10^{-5}$  c/cm<sup>3</sup> and it is this that sets the upper limit of concentration. This means that the highest beta counting rate possible is about 3000 per min (with standard error of about  $\pm 2$  per cent for one minute periods).

II:6(e). *Other measurement methods*—Some other tracer methods which have been used or suggested, sometimes for other applications, are briefly discussed below.

*Acoustic analyser.* Geburth[29]; Griffiths[30]; Haswell and Reid[31]; Molynieux[32] and Reid[33].

Anaesthetic concentrations have been measured from determinations of the speed of sound of the mixture. Several instruments have been described which could be used to make the necessary measurements, easily and quickly, and there is at least one commercial instrument which can be used continuously. This instrument will give full-scale deflection for 15% argon or 7% carbon dioxide or 4.5% helium or hydrogen (all percentages by volume) and thus would not be using more than one quarter of its range in ventilation tests.

*Hygrometers.* Dufton and Marley[34] and Wexler[35].

The use of hygrometers is usually inadvisable because of the poor qualities of water vapour as a tracer. It tends to be absorbed (or given off) by many materials, is likely to condense on window panes in cold weather and is often produced in a room. In addition to the hair hygrometers and wet and dry bulb thermometers used in routine meteorological measurements, several other techniques have been used to determine water vapour content. These include wet and dry bulb resistance thermometers, wet and dry bulb thermocouples, infra-red absorption, ion-exchange transducers and humidity sensitive capacitors and resistors and electrolytic methods.

*Ultra-violet absorption.* Bourdillon *et al.*[36] and Lidwell and Lovelock[19].

The use of u.v. absorption to measure concentration of organic vapours has been recorded by Lidwell and Lovelock[19]. Two vapours, namely acetyl acetone and ethyl acetoacetate were found to hold promise for this purpose, the accuracy to which the concentrations could be measured being about 0.06 mg/ft<sup>3</sup> and 0.22 mg/ft<sup>3</sup> respectively. The principle is used in industry for the measurement of chlorine concentrations.

*Particulate tracers and aerosols.* Dimmick[37] and Dumbould[38].

This type of tracer can be used satisfactorily only if the particle size is so small that the particles remain airborne for a fairly long time. Such tracers that have been used for meteorological purposes have diameters of the order of two or three microns and can be detected by fluorescent means, in concentrations as low as 10<sup>-10</sup> g/ml. The terminal velocity of such particles is about 3 ft/h. One can also estimate the concentration of a particular

tracer by light scatter techniques (which are very sensitive when photo-multipliers are used) or by counting the concentration on a microscope slide from an impingement dust sampler.

To some extent, all studies of airborne bacteria dispersal are particulate tracer studies (in fact tracer gases have been used to simulate the problem) and this is especially true of the method employed by Dimmick[37] who bred bacteria whose phosphorus content was wholly of a radio-active isotope. Then, even if the bacteria were killed or multiplied, the total mass of radio-active matter stayed constant and could only be removed (apart from radio-active decay) by physical displacement from the experimental area.

*Paramagnetism.*

Oxygen concentrations can be accurately measured by its unusual property (for a gas) of being strongly paramagnetic. Commercial instruments exist which can determine oxygen concentrations to  $\pm 0.025$  per cent. The principle is not applicable practically to other gases and oxygen is not the ideal tracer in occupied rooms.

## II:7. Experimental comparison of measurement techniques

Estimated accuracies, based on practical experience of the use of tracer gases, have only been published for the rate of decay method (which is by far the most widely used method).

Renbourn *et al.*[16] observed that successive estimates (at hourly intervals) of natural ventilation airchange rates in the range 1-3 changes/h could vary by up to 0.8 changes/h.

Van Straaten[21] found that below 1 change/h, unless the air was mixed by a fan, non-logarithmic decay of tracer took place.

Table 2. Experimental accuracies of rate-of-decay methods (all sources of error)

Gas and measurement technique	Mean rate	Estimated error (%)	Observer	Notes
CO <sub>2</sub> chemical analysis	0.80	$\pm 15$	Renbourn <i>et al.</i> [16]	2 std. devs.
CO <sub>2</sub> chemical analysis	1.80	$\pm 11$	Renbourn <i>et al.</i> [16]	2 std. devs.
CO <sub>2</sub> katharometer	1.83	$\pm 12$	Renbourn <i>et al.</i> [16]	2 std. devs.
H <sub>2</sub> katharometer	—	$\pm 15$	Van Straaten[21]	field conditions
H <sub>2</sub> katharometer	—	$\pm 7$	Van Straaten[21]	steady lab. conditions

Table 3. Simultaneous estimates by rate of decay and gas flow methods

Tracer gas	Tracer measurement method	Gas flow measurement method	Mean estimate (ch/h)	Difference between methods (%)	Observer	Notes
H <sub>2</sub>	katharometer	orifice plate	7.08	+1 <sup>N</sup>	Marley[24]	No mixing
H <sub>2</sub>	katharometer	orifice plate	4.09	5.6	Van Straaten[21]	No mixing
H <sub>2</sub>	katharometer	orifice plate	0.51	+10 <sup>S</sup>	Van Straaten[21]	Fan used initially
H <sub>2</sub>	katharometer	orifice plate	1.07	+7.8 <sup>S</sup>	Van Straaten[21]	Fan used initially
H <sub>2</sub>	katharometer	orifice plate	1.83	+1.9 <sup>N</sup>	Van Straaten[21]	Fan used initially
H <sub>2</sub>	katharometer	orifice plate	3.72	-0.5 <sup>N</sup>	Van Straaten[21]	Fan used initially
H <sub>2</sub>	katharometer	orifice plate	6.45	-2.1 <sup>S</sup>	Van Straaten[21]	Fan used initially
H <sub>2</sub>	katharometer	orifice plate	8.00	-1.8 <sup>S</sup>	Van Straaten[21]	Fan used initially
H <sub>2</sub>	katharometer	orifice plate	7.37	-3.4 <sup>N</sup>	Marley[24]	Fan used initially
H <sub>2</sub>	katharometer	orifice plate	7.73	+3.2 <sup>N</sup>	Marley[24]	Fan used initially
H <sub>2</sub>	katharometer	orifice plate	4.05	+2.5 <sup>N</sup>	Marley[24]	Fan used initially
H <sub>2</sub>	katharometer	meter	—	5	Bastings[8]	
Coal gas	katharometer	gas meter	3.33	3.9	Warner[17]	In iron tank
N <sub>2</sub> O	i.r. absorption	gas flow	14.5	3.4	Lidwell[7]	

The differences may be due to systematic or random errors. A plus sign before the difference indicates that the tracer estimate was the higher of the two, a minus sign, that it was the lower. A superscript *N* denotes a difference which is not significant at the 1 per cent level (bearing in mind the uncertainties of the estimates), a superscript *S* denotes one which is. Omission of a sign or superscript indicates that the sense or significance of the difference is unknown. Differences are expressed as percentages of the mean estimate.

Table 4. Simultaneous estimates by two tracer gases (Both using rate of decay methods)

'First' gas and measurement method	'Second' gas and measurement method	Mean estimate (ch/h)	Difference between estimates (%)	Observer
H <sub>2</sub> katharometer	<sup>41</sup> A geiger counter	1.15	+8.7	Collins <i>et al.</i> [28]
H <sub>2</sub> katharometer	<sup>41</sup> A geiger counter	2.90	+6.9	Collins <i>et al.</i> [28]
CO <sub>2</sub> chemical analysis	<sup>85</sup> Kr geiger counter	7625 ft <sup>3</sup> /min	-8.5	Howland <i>et al.</i> [6]
CO <sub>2</sub> chemical analysis	<sup>85</sup> Kr geiger counter	10450 ft <sup>3</sup> /min	0	Howland <i>et al.</i> [6]
CO <sub>2</sub> chemical analysis	<sup>85</sup> Kr geiger counter	4400 ft <sup>3</sup> /min	+9.1	Howland <i>et al.</i> [6]
CO <sub>2</sub> chemical analysis	coal gas katharometer	0.15	+3.3	Warner[17]
CO <sub>2</sub> chemical analysis	coal gas katharometer	0.25	+20	Warner[17]
CO <sub>2</sub> chemical analysis	coal gas katharometer	0.47	-2.1	Warner[17]
N <sub>2</sub> O i.r. absorption	C <sub>3</sub> H <sub>6</sub> O chemical analysis	5.85	3.6	Lidwell[7]

A positive sign denotes that the 'First' method gave the higher estimate, a negative sign that the 'Second' did. No sign means that the sense of the difference is unknown.

Table 5. Simultaneous estimates using two methods of measuring the same tracer gas

Gas	'First' measurement method	'Second' measurement method	Mean estimate (ch/h)	Difference between estimates (%)	Observer
CO <sub>2</sub>	chemical analysis	katharometer	1.82	-1.6	Renbourn <i>et al.</i> [16]
He	katharometer	thermistor katharometer	3.21	-1.3	Coblentz and Achenbach[11]

The sign convention is as for Table 4.

Table 6. Rate of decay tracer method and indirect estimates

By making assumptions of the rate of heat or moisture production and losses other than by ventilation, it is possible to estimate the ventilation rate from measurements of temperature or humidity differences between internal and external air. The method is, in general, not to be recommended as the assumptions are rarely reliable enough for the ventilation rate estimate to be more than a rough figure.

Gas and measurement method	Mean estimate (ch/h)	Difference from mean			Observer
		Tracer method (%)	Heat balance (%)	Moisture balance (%)	
Unknown	19.1	-5.8	+11.5	-6.3	Smith[39]
possibly	43.4	-7.8	+3.9	+5.1	Smith[39]
<sup>85</sup> Kr	12.2	+6.5	+8.2	-15.6	Smith[39]

These observations were made in animal houses with forced ventilation. Differences are again expressed as percentages of the mean estimate of the airchange rate.

## II:8. Tracer gases for use in occupied rooms

II:8(a). *Desirable properties of tracer substances (all methods)*—The properties should be held at the low concentrations used.

Physical: similar density to air, similar specific heat to air, similar diffusion properties to air (i.e. similar molecular weight), not likely to condense in room conditions.

Chemical: non-explosive, unreactive with constituents of air or with anything in the test area, stable in room conditions.

Physiological: odourless, non-irritant, non-toxic (if to be used in occupied rooms). Colourless (preferably).

Other: not produced in test area, steady natural concentration, detectable quantitatively at low concentration, readily available.

For decay rate measurements it is also desirable (if impractical) for the tracer to spread throughout the test area quickly, without otherwise changing the airflow.

## II:8(b). Summary of tracer gases.

Table 7

Vapour or gas	Density compared to dry air at NTP	Maximum concentration possible (% by vol)	Top limit to concentration	Minimum concentration detectable (% by vol)	Method of measurement of minimum	Notes
Hydrogen (H <sub>2</sub> )	0.07	1.1	a	0.02	i	I
Helium (He)	0.14	1.2	a	0.03	i	
Water gas (H <sub>2</sub> and CO)	0.5	0.08 (2)	d (a)	0.001	iii	I II III
Water vapour (H <sub>2</sub> O)	0.6	2.5	a	0.2	iii	IV
Ammonia (NH <sub>3</sub> )	0.6	10 <sup>-3</sup> (2.5)	d (a)	~10 <sup>-4</sup>	vi	I III
Carbon monoxide (CO)	1.0	0.04 (13)	d (b)	0.0005	iii	I III
Ethane (C <sub>2</sub> H <sub>6</sub> )	1.0	2.5	b	0.5	i	I
Argon ( <sup>41</sup> A)	1.4	~10 <sup>-10</sup>	c	~10 <sup>-9</sup>	ii	
Carbon dioxide (CO <sub>2</sub> )	1.5	2	a & d	0.0001	iii	IV
Nitrous oxide (N <sub>2</sub> O)	1.5	2	a	0.0001	iii	
Acetone (C <sub>3</sub> H <sub>6</sub> O)	2.0	1	a	0.01	iv	II
Krypton ( <sup>85</sup> Kr)	2.9	~10 <sup>-10</sup>	c	~10 <sup>-9</sup>	ii	
Chloroform (CHCl <sub>3</sub> )	4.2	0.001 (0.3)	d (a)	0.05	v	III
Xenon ( <sup>133</sup> Xe)	4.6	~10 <sup>-10</sup>	c	~10 <sup>-9</sup>	ii	

Key: a—To maintain density of air/tracer mixture within 1 per cent of air density  
 b—Inflammable limit  
 c—Permissible radiation level in occupied area  
 d—Maximum safe concentration for occupied area  
 i—Katharometer  
 ii—Geiger counter  
 iii—Infra-red absorption

v—Analysis  
 vi—Acoustic  
 vi—Colorimetric  
 I—Combustible (but not inflammable at these concentrations)  
 II—Odour  
 III—Toxic  
 IV—Unsteady background concentration



absence of high temperatures, nitrous oxide measured by i.r. analysis offers a wider range of useable concentrations, but hydrogen, measured with a katharometer has much the lowest cost (and a range of concentrations similar to that of helium). The graph (figure 1) shows, roughly, the relative costs of the methods (at Liverpool at the end of 1965), together with some other combinations of gas and detectors. No allowance has been made on this graph for the hire or purchase of gas cylinders, but the cost of apparatus to sample gas from several points in the room has been added to the basic measuring equipment cost where necessary. There is a minimum charge for radioactive tracers and as these are in break seal ampoules, and in any case not suitable for long storage, each test is assumed to cost this minimum. In most cases, a considerably greater quantity of tracer would be purchased for the same price, if a larger volume was to be investigated. The hypothetical test on which the graph is based is of producing a tracer concentration ten times higher than the minimum detectable in a room of 5 000 ft<sup>3</sup> volume. If larger volumes of tracer are required (either to increase concentration or because of a larger test volume) the gradients of the lines will increase.

### III. AIR MOVEMENT MEASUREMENT

#### III:1. Introduction

Measurements of airspeed and direction of motion can be helpful in the study of natural ventilation as they provide knowledge of the pattern of air movement within a room and the flow through apertures to the outside or to other parts of the building. Visible tracers and airspeed measurements can quite quickly give a broad picture of the general flow patterns, which can be 'filled in' in more detail by tracer techniques.

The most obvious special feature of airflow in natural ventilation measurements is that it is very slow—less than one foot per second as a rule. Many and varied are the methods by which attempts have been made to measure such speeds, and this section is, of necessity, only a brief outline of the more well-known techniques.

#### III:2. Determination of airflow patterns

There are two basic techniques which can be used to determine the airflow pattern (that is, the positions and directions of the principal currents) in a room. One can either use indicators of air movement which stay at the same place in the room or one can introduce visible materials which to a greater or lesser extent follow the airflow.

##### III:2(a). Fixed indicators; Grime[49].

Small mica vanes have been used[49] to determine the horizontal components of air motion. These are very sensitive but are slow to settle down to a steady direction, and are rather fragile.

Silk threads about 6 in long, teased out into fine filaments are less sensitive but less likely to be damaged. Although strong upward currents can be detected they are more useful as indicators of horizontal motion. Circumstantial evidence from other measurements (such as air temperature) may give some indication of the airflow pattern.

##### III:2(b). Moving indicators; Dick[12], Grime[49], Daws[50], Givoni[51] and Smith[52].

Various smokes have been used to show the positions of air currents, notably ammonium chloride[12], titanium tetrachloride[49, 52], evaporated paraffin-oil mixture[51] and, of course, tobacco smoke[49]. In common with all moving indicators, none of these has exactly the same density as air and very light vertical currents may not be followed. In practice, this is not a very severe limitation to their use. Grime[49] has recorded that in slight vertical motions, rings of titanium tetrachloride broke away and drifted downwards, while the rest of the smoke rose upwards. Small particles of metaldehyde will stay airborne for over an hour indoors and this material has been used in test rooms[50]. Air motion in models has been observed using soap bubbles[51] as an indicator, and there seems no obvious reason why they should not be used in field measurements.

On a larger scale, gas-filled rubber balloons, weighted to have neutral buoyancy in still air have been used, particularly in large halls[49]. The advantage of this method is that currents can be traced over greater distances in each test than is possible with other methods. Perfect balance is impossible and very slow air currents cannot be reliably traced. Neither is the method very good for tracing narrow, fast air streams as they generally deflect the balloon away from the stream. Another disadvantage is that the balloon readily acquires an electric charge and is then attracted to walls and furniture.

#### III:3. Drag anemometers and dynamic pressure measurements

##### III:3(a). Drag anemometer; Head and Surrey[53], Kemp[54], and Rees[55].

A drag anemometer consists basically of a simple body exposed to the airstream, the drag force of which is measured. The simplest form in principle is to measure the deflection of a freely hanging plate. In practice, this is not very satisfactory because the drag on a plate varies considerably with the angle of incidence of the impinging airflow. In the other form of the instrument the plate is maintained normal to the airflow and the force needed to do this measured. Plates, as opposed to three-dimensional shapes are useful for this type of instrument because they are sensitive to low airspeeds, less affected by small incidence changes than many bodies and are more consistent in their

calibration, being largely free from scale effects. Simple plates tend to have rather uncertain calibration probably due to movement of the centre of pressure and an asymmetric shape (such as a disc with an offset hole in it) is much more consistent.

Drag anemometers have been used in wind tunnels[53, 54] and in mines[55] to measure airspeeds between 0.2 ft/s and 16 ft/s, in the former case to repeatabilities of 1.2 per cent. These are both uses where the direction of airflow is well established and the plate can be set perpendicular to it. Since the area of the drag plate is normally several square inches, any reading must be some sort of average over this (or a larger) area and the airflow nearby must be affected by the presence of the instrument.

The response time of the plate to fluctuations depends on the size and shape of the plate and stiffness of the suspension. The speed with which measurements can be made is often limited in anemometers of this type by the fact that the adjustment of the plate to a vertical position is done manually by adjusting counter weights or the torsion of springs or an electric current. Spherical drag anemometers using strain gauges to detect small displacements have been used to measure turbulence of the surface wind[56] and while their lower limit of airspeed has been about 25 ft/s the response to rapid fluctuations is very good.

#### III:3(b). *Dynamic pressure measurements*; Ower[57].

Wind pressure transducers, as used on buildings to measure wind speeds and forces, operate on the principle of detecting a small displacement caused by the dynamic pressure of the wind but are by no means sensitive enough for the magnitudes involved in ventilation.

The pitot-tube and manometer is, according to Ower[57] not reliable below about 15 ft/s. Modern micromanometers, using electronic techniques to detect small displacements of diaphragms have claimed accuracies which would correspond to about  $\pm 0.04$  ft/s (i.e. would be  $\pm 4$  per cent of 1 ft/s) which is a distinct improvement on his estimate. The pressure-tube is highly directional.

#### III:3(c). *Velometer*; Ower[57], Poole and Leadbeater[58].

Another instrument that comes into this general category is the velometer[57, 58]. This is essentially a pivoted, spring-controlled aluminium vane mounted in a chamber of a shape such that, as the vane pivots the gap between the vane and the side of the chamber changes. The space on one side of the vane is open to the atmosphere and the other side is connected to a tube facing the airflow. The shape of the chamber is designed so that the vane deflection is linearly related to airspeed. The normal instrument is useable down to about 0.5 ft/s and a special instrument incorporating eddy-current damping and reduced friction pivots has been used to measure speeds down to 0.1 ft/s. The indicated airspeed is largely independent of the direction of

airflow over a range of  $\pm 30^\circ$  from the true direction. The instrument is easy and quick to use.

#### III:4. *Rotating anemometers*

Rotating anemometers fall into two main types; those that rotate about an axis perpendicular to the airflow direction and those whose axis of rotation is parallel to the airflow (i.e. in general; 'cup' and 'vane' anemometers).

##### III:4(a). *Cup anemometers*; Jones[59].

A cup anemometer comprises a number of hollow cups attached around a spindle, to which an indicator of some kind is fitted. Since the wind force on the concave side of a cup is greater than on the convex side for the same wind speed, the shaft rotates. This type of instrument is widely used in meteorological studies but most of the instruments designed for such use are not at all sensitive to very low airspeeds. There are, however, one or two (e.g. [59]) whose 'threshold' airspeed is 0.7–0.8 ft/s, including at least one which is a commercial product. These low-speed cup anemometers employ six or more lightweight cups and non-mechanical sensors of the shaft rotation (either photo-electric or capacitance change). Since they are 8 in. or more in diameter, errors will be introduced by spatial variations in airflow. Temporal variations also introduce some inaccuracies as this type of instrument tends to respond more **quickly** to increases of speed than to decreases. This last comment applies less strongly to these lightweight anemometers than to the traditional meteorological type. They are normally accurate to about  $\pm 0.2$  ft/s for airflow directions within  $\pm 10^\circ$  of the horizontal.

##### III:4(b). *Vane and propeller anemometers*; Holmes *et al.*[60] and Ower[57, 61].

Vane and propeller anemometers for low-speed measurements usually have about 8 flat blades. The general principle is, as the name suggests, that of an airscrew. The limitations are usually caused by gear friction and limit the traditional type of commercially produced instruments to speeds above 1 ft/s. Ower[57, 61] developed a low friction variation which was useable almost down to 0.5 ft/s and there is a commercial instrument which by elimination of the gearing and using a capacitance change pickup is claimed to be useable slightly below 0.5 ft/s. One design of small propeller anemometer designed for outdoor use is also sensitive down to about 0.8 ft/s[60]. At these low extremes, the calibration is usually consistent but not linear. The speed of response is apparently a function of the airspeed, improving with an increase in speed. Since the small outdoor anemometer mentioned above has a time constant of several seconds at its lowest extreme, it would appear likely that the other instruments will be little better. As they are usually used to measure time averages, this is not a severe drawback in normal use.

Spatially, they obviously indicate a speed which is some sort of average over the cross-section of the vane (usually about 7–12 in<sup>2</sup>) and must affect the airflow to some extent. The response to airflows not parallel to the axis of rotation is, for the outdoor propeller type, close to a cosine law.

### III:5. Thermal anemometers

There are a number of types of thermal anemometers, most (but not all) based on the measurement of the rate of loss of heat. All heated instruments have a tendency to induce convection currents, which at low incident airspeeds may be of similar magnitude to the measured variable. This feature is more marked with the higher temperature instruments.

#### III:5(a). *Kata* thermometers; Bedford and Warner[62], Dufton[63], Koch and Kaplan[64].

These have been in use for over 150 years. A thermometer with a large bulb (over  $\frac{1}{2}$  in. diameter) and usually alcohol-filled is warmed to a temperature above air temperature. From the time taken for a known temperature drop and the air temperature, the airspeed can be derived. To reduce radiant heat transfer, the bulb is silver or rhodium plated. The calibration curve is non-linear but is consistent; it does, however, change with the mode of airflow around the instrument and requires three different formulae to fit the curve over different speed ranges. The time response is clearly slow due to the size of the bulb, but in any case the sampling time is determined by the airspeed. The lower limit for reliable measurements is about 0.2 ft/s and the thermometer is not directionally sensitive. In rather extreme radiant conditions errors of 3 per cent have been observed. The principal advantage that it offers is great simplicity of use.

#### III:5(b). *Heated thermometer anemometers*; Long[65], Yaglou[66].

If a heater coil is wound round the bulb of a standard thermometer and a steady power input applied, the temperature difference above the air to which the thermometer rises is an indication of the airspeed. A range of velocities of from 0.2 ft/s to 100 ft/s can be measured, several different heater powers being used for different parts of the range. Although the smaller bulb improves temporal and spatial resolution compared to the *Kata*, the time constant is still of the order of half a minute or more and the cross-section of the bulb exposed to the air is rather more than 0.1 in<sup>2</sup>. By the use of aluminium paint or foil, the effects of high radiant heat intensities can be greatly diminished. Directionally, the instrument is insensitive to changes of airflow direction within a range of about  $\pm 30^\circ$  from a plane perpendicular to the axis of the thermometer. While the self-convection is small (temperature differences of only 10–20 deg F between air and instrument being normal) at low

vertical airspeeds (i.e. about 1 ft/s) there is about 6 per cent difference between estimations of equal upward and downwards flow. At higher airspeeds this is less marked. The overall accuracy is, according to Yaglou[66] about  $\pm 2$  per cent in laboratory conditions and up to  $\pm 4$  per cent in the field.

A variation, using a low temperature 'bulb' of similar size but using an electric resistance thermometer instead of a mercury-in-glass system was used by Long[65]. This instrument was also useable down to about 0.2 ft/s.

#### III:5(c). *Hot-wire anemometers*; Anderson[67], Deacon and Samuel[68], Krishnaswamy[69], Penman and Long[70], Rasmussen[71], Simmons[72], and Willis[73].

The basic principle of this type of instrument is the same as the heated thermometer anemometer but the sensing element is very much smaller. The heated body is a fine platinum or nichrome wire, typically about  $\frac{1}{2}$  in. long and 0.01 in. dia. The operating temperature may be up to about 700°F but for low-speed versions is likely to be below 250°F. The wire may be enclosed in a silica tube as suggested by Simmons[72] or may be exposed directly to the airstream. The latter arrangement has the disadvantages of fragility and variation of calibration. If the wire is unshielded, its temperature is deduced from its resistance and there is no reason why this method cannot be applied to shielded instruments. Simmons, however, used a double-bore silica tube and inserted a fine thermocouple into the second bore. For greatest accuracy the instrument should be operated with the axis of the wire perpendicular to the airflow and at low airspeeds with the axis vertical. Under these conditions, the Simmons type (which runs at a relatively low temperature and is thus less affected by self convection) can be used down to about 0.1 ft/s. The accuracy claimed is  $\pm 0.7$  per cent at 0.4 ft/s (which corresponds to about  $\pm 3$  per cent of 0.1 ft/s). Within  $\pm 30^\circ$  of the normal to the axis, the response to non-perpendicular directions of airflow approximately follows a cosine law. An exposed-wire anemometer, using a thermocouple soldered to the hot wire has been used to measure airspeeds inside clothing down to about 0.07 ft/s[69]. The hot-wire in this case was only about 5 deg C above the ambient temperature. The calibration remained proportional to the square root of the airspeed. Hot-wire anemometers are used to measure high frequency fluctuations in turbulence measurements, which is outside the scope of this account, but time constants of the order of milli-seconds are quite possible. There are two modes of operation of hot-wires: constant temperature and constant current. The latter requires simpler ancillary equipment than the former, but is limited in use to low intensity turbulence, which, of course, is the usual situation in ventilation airflow. The remote reading nature of the instrument makes it very

suitable for situations where simultaneous readings are required. A variation on the method is the use of a hot film instead of a wire.

Another hot-wire technique for determining low airspeeds that has recently been suggested and demonstrated as feasible[71] makes use of the fact that the calibration is not linear. This means that the sensitivity of the instrument to oscillating air movement varies with the net flow. Thus, if the anemometer is operated in a constant sound field, the amplitude of the a.c. portion of the instrument signal is a function of the (net) air velocity. Such an a.c. signal is easily amplified, and is less variable with changes of air temperature than the usual d.c. signal. The calibration is, however, ambiguous unless it is known that the airspeed is either above or below about 1 ft/s. In doubtful cases, this can be resolved by changing the sound frequency. With this proviso, speeds down to 0.2 ft/s can be measured.

Thermistors[70] have been used instead of resistance wires. These have a much greater rate of change of resistance with respect to temperature, and the type that are usually used as anemometers are heated to temperatures of 200–400°F.

III:5(d). *Hot grid anemometers*; Baird[74], Benseman and Hart[75], Kemp[76], Sexton[77] and Taylor[78].

These are really another form of hot-wire anemometers. If the hot wire and the temperature sensing device are separated, and the heater placed between the two thermometers (resistance or thermocouple), one being a little upstream and one downstream, then the temperature difference between them is dependent on the airspeed. Furthermore, the instrument is directionally sensitive and indicates the polarity of the flow. This was essentially the layout used by Taylor[78] to measure the vertical component of wind in the lowest layers of the atmosphere. The more common arrangement is to mount a heater grid in a cowl and use a grid of resistance wire or thermocouples equispaced from the heater in the cowl. Thermocouples are usually used, because by connecting the grids in series an output proportional to the temperature difference is produced. Unfortunately, the calibration exhibits a peak due to convective effects of the heater. As long as it is known whether the airspeed is above or below the critical velocity at which this peak appears, unambiguous results can be produced. There are two approaches to the design of such an instrument, either the critical velocity can be reduced as much as possible (in practice it can be reduced to about 0.25 ft/s) or it can be raised and the high sensitivity region between zero and the critical velocity used (this can certainly be raised to 2 ft/s). If the second approach is used, other methods can more easily be used to determine approximate airspeeds and thus which section of the calibration is relevant. With a low critical speed, airspeeds down to 0.3 ft/s[75] may be measured, and with a high critical speed the lower limit is, remarkably, only 0.01 ft/s[75]. (Although the figures noted

here are airspeeds, this type of instrument is often used, and therefore calibrated, as a volume flow meter.) The time constant is, typically, about 0.5 s. The response to airflow off the axis of the cowl depends on the particular cowl design but, with the aid of flow straighteners, can be made to follow a cosine law over about  $\pm 30^\circ$ . The cross-sectional area of instruments varies from  $\sim 1$  in<sup>2</sup> to  $\sim 70$  in<sup>2</sup>. This type of instrument is relatively unaffected by dirt and dust, or by changes of air temperature.

III:5(e). *Sinusoidally heated hot-wire anemometer*; Walker and Westenberg[79].

If a wire is heated in a time-varying manner, the temperature of the air varies spatially in a manner which is a function of the airspeed. If the heating is sinusoidal (with mean value such that it is never zero) then this pattern is also sinusoidal and the wavelength is a measure of the airspeed. By comparing the (a.c.) input to the heater to the fluctuations of air temperature at an adjustable point downstream (for example by producing Lissajous figures on an oscilloscope) the phase lag of the detector with respect to the heater can be found. The detector can be moved until the phase angle is increased by  $180^\circ$  and the wavelength and thus the airspeed determined. Walker and Westenberg[79] used a heater current of about 100 c/s frequency and detected accurately  $18^\circ$  phase angle changes. This gave them accuracies of about  $\pm 2$  per cent compared to particle-track measurements. The lowest speed that they could measure was  $\sim 1.2$  ft/s. The method is clearly very directional and only suitable for slow-changing conditions. The value produced is an average over the  $\frac{1}{4}$  in. or so between two detector positions. Walker and Westenberg also tried the alternative method of varying the heater frequency instead of moving the detector. They found that difficulties were encountered because of thermal lag of heater and detector, the need for more sophisticated phase measuring devices and the fact that part of the distance over which the speed is averaged is always in the wake of the heater.

III:6. *Other low-speed anemometers*

III:6(a). *Ionization anemometer*; Lovelock and Wasilewska[80], and Welman[81].

In a moderate electric field, the movement of ions through air is slow enough to be considerably affected by air movement. Furthermore, the motion of positive ions is little influenced by changes of humidity. Lovelock and Wasilewska[80] have described an anemometer based on this observation. A source of  $\alpha$  particles at 120 V was placed at the centre of an earthed grid. By measuring the current which flowed between source and grid, the airspeed could be inferred. The grid was of sufficient size to surround all the ions produced in the air by the alpha particles. The very small currents (about  $10^{-9}$  A) have to be amplified and

the resulting instrument is sensitive to speeds down to 0.15 ft/s at least. Within about  $\pm 30^\circ$  of the horizontal plane and for all directions in the plane, the calibration is accurate to about  $\pm 3$  per cent. Although the radioactivity is quite low (a  $\beta$  and  $\gamma$  dosage of about 20 mrad/h at 1 ft is quoted) care has to be taken in use.

### III:6(b). Laser anemometer; Maceck *et al.*[82].

The velocity of light through a moving medium changes with the speed of the medium. This effect can be put to use as an anemometer. It has in fact been used to check the accuracy of predicted changes in light velocity in air moving at speeds greater than 16 ft/s and it has been stated that there is no reason why a more sophisticated instrument should not have sensitivities of less than 0.01 ft/s. The measured speed is an average over the full air path length and airspeed components along one axis only are measured on one instrument. The passage of light causes no interference (on a practical scale) to the airflow, and the time response to changes should be very rapid.

### III:6(c). Sonic anemometers; Kaimel and Businger [83].

If the velocities of two sonic signals travelling in opposite directions between two points are known, the airspeed can be deduced. Several instruments have been built which utilise this fact. One[83] in which phase shifts due to the different path lengths are used to determine the transit times is accurate to  $\pm 4$  per cent over a range of about  $\pm 16$  ft/s, and could presumably be used to detect airspeeds down to about 0.6 ft/s. The airspeed found is an average over the air path length.

### III:7. Anemometers useable below 1 ft/s

Table 9

Limiting airspeed (ft/s)		Reference
0.01	Low-speed hot grid	[75]
0.07	Exposed hot wire	[69]
0.1	Shielded hot wire	[72]
	Low-speed velometer	[58]
0.15	Ionization	[81]
0.2	Hot wire microphone	[71]
	Kata	[62, 64]
	Heated bulb	[65, 66]
	Drag plate	[53, 54]
0.25	Hot grid	[74]
0.5	Velometer	[57]
	Low-speed vane	[57]
0.7	Low-speed cup	[83]

## IV. MODEL TECHNIQUES

### IV:1. Introduction

When it is difficult or impossible to make field measurements on the scale required for a particular

investigation (perhaps because of non-transportable equipment, or because a building exists only on paper) progress can be made by simulation techniques. This approach is particularly useful for design purposes, since it is usually relatively easy to make alterations to conditions.

This section will deal with techniques which involve laboratory measurements. All ex-field methods rely to some extent on assumptions about conditions in the field, ranging from the relatively few assumptions of a full-scale model to the underlying assumptions on which hypothetical calculations are based. With this in mind, it is clear that any simulation or calculation method must be proved against field measurements before it can be relied upon.

### IV:2. Full size replicas

The occasions when it is worthwhile to build a full size replica of a room or system of rooms are obviously going to be few and far between, and no applications of this method have been published. On the other hand special rooms and buildings for the investigation of various aspects of ventilation have been built. Although the techniques of field measurements can be applied in these rooms, their value lies in the ability to incorporate special devices, such as transparent walls or the ability to alter the form or orientation of the room, or in the case of dwellings, to incorporate special measurement devices.

### IV:3. Scale models

The principal problem with scale models is that, in general, different physical phenomena are affected to different extents by a change of scale. In the case of ventilation, the physical processes of most interest (and those which must be modelled most accurately) are those of airflow and heat transfer. This means that ideally, one would like to balance buoyancy, viscous and inertia forces of the airflow and heat flow by radiation, convection (natural and forced) and conduction. In actual application, some of these may be unimportant and others may be interrelated in such a way that a change in one variable may cause a predictable change in others. Since only a certain number of factors are under the experimenters control (at best the fluid material, the model material, surface finishes, fluid speed, temperature, model scale) a certain degree of compromise is inevitable.

### IV:3(a). Wind-induced ventilation; Givoni[51], Smith[52], and Wannenburg and Van Straaten[84].

In order to produce the same airflow pattern around a model as around a full size object, it is normally necessary to use test conditions such that the Reynolds number of the model flow is the same as that of the real flow. The Reynolds number is an indication of the ratio of inertia to viscous forces in the fluid flow and is dependent on the density, viscosity and speed of the fluid and on the linear

size of the model. However, in model studies of buildings it is usually inconvenient if not impossible to produce the correct value of the number. Fortunately, objects with sharp corners and plane surfaces tend to produce much the same flow pattern over a wide range of airspeeds, and it has been demonstrated that airflow and pressure distribution outside a building are realistically modelled, provided that the Reynolds number is greater than a critical value (although much lower than the full size value[52, 84]). The actual parameter used by Smith[52] was  $E = (2Av)/P$  where  $A$  is the area of the building, normal to the flow  $P$  is the perimeter round which the air must flow and  $v$  is the airspeed well away from the building. The critical value was about  $E = 2000$  ( $A$ ,  $P$  in in<sup>2</sup> and inches respectively,  $v$  in ft/min). As an example of orders of magnitude, for a 6 in. cube, the minimum velocity to satisfy this condition is 500 ft/min, for a 5 ft cube it is 50 ft/min and for a 50 ft cube only 5 ft/min. Whether any equivalent criterion exists for indoor flow is unknown.

Smith[52] compared airflow patterns in a model and a full size experimental building and noted that 'Most of the . . . . . patterns gave the same airflow pattern in the models that they had given in the experimental building'. By 'airflow pattern' he meant the pattern of airflow paths as determined by a smoke tracer. No airspeed measurements are quoted. One important point that he noticed was that small inaccuracies of the model (corresponding to a 2 in. displacement of a window edge in the full size) could cause major changes in the airflow pattern. Givoni[51] gives some results of a test in which airspeeds on a plane across a model room were measured for several windspeeds, all from the same direction. His verdict was that internal velocity distributions were similar for various external velocities and that the average velocity remained at an 'almost constant' percentage of the external velocity, and he went on to investigate in a similar manner, the effect of various window configurations. In fact the average internal velocity varied from 15 to 18 per cent of the external airspeed, that is it varied by about  $\pm 10$  per cent of its mean value. He took four readings at each of 25 sites in the model at 7 different external velocities. At particular sites, the four-reading averages had r.m.s. deviations of from 5 per cent to over 20 per cent of their mean values. ('Values' in the context of his experiments being the internal velocity expressed as percentages of the external velocity.) Thus, while the general flow pattern appeared more or less constant, there were quite large variations in the relative airspeeds at different points in the model. As a check on the constancy of the pattern, the 25 readings of each test have been ranked in decreasing order of magnitude and the coefficient of concordance between the tests calculated as if each test was an independent estimate of the pattern. The coefficient was 0.65, which indicates a high degree of resemblance between the rankings.

Thus, to summarize, published accounts of model studies of wind induced ventilation show that, provided that the model is accurate, general patterns of airflow can be reliably predicted but actual internal airspeeds cannot. As far as can be ascertained, the models mentioned above did not include furniture or occupants and no attempt was made to reproduce the wind gradient or turbulence. Several other authors have tackled the problems of the effect of turbulence and pointed out the relevance of their studies to model studies of ventilation (for example, several authors mentioned by Pocock[85]).

The estimation of pressures around buildings by model techniques is fairly well established and from such data it may well be possible to infer air movement into and out of a building with reasonable confidence, although the intra-building flow may be unknown. This has not been checked experimentally.

IV:3(b). *Thermally induced ventilation*; Focken[86], Jakob[87], Parczewski and Renzi[88], Rankine[89], and Rydberg[90].

The problem of modelling thermally induced ventilation is complicated by the need to simulate the temperature distribution of the model as well as the convective airflow. In the case of modelling of a real building it may be possible to reproduce the temperature distribution by heaters embedded in the model, but for design studies this is unlikely to be possible and the model must be thermally accurate as far as is possible.

Even with steady conditions it is rarely possible to scale thermal effects accurately because different processes obey different scaling laws. It is possible to compensate for some errors by distorting the physical model materials. The following table (based largely on data in Parczewski and Renzi[88]) shows how the heat flow from a surface changes when the two principal variables undergo a scale change.

Table 10

Scale change of:	Length	Temperature
Mode of flow	(L)	( $\theta$ )
Radiation	$L^2$	$\theta^4$
Forced convection:		
Laminar flow	$L^{3/2}$	$\theta$
Turbulent flow	$L^{9/5}$	$\theta$
Natural convection:		
Laminar flow	$L^{7/4}$	$\theta^{1/4}$
Turbulent flow	$L^2$	$\theta^{1/3}$
Steady conduction	$L$	$\theta$

When equilibrium conditions do not exist, time scaling may be necessary. The modelling of airflow, when thermal effects are present, is extremely complex. According to Jakob[87], in order to

model free convection completely, there are twelve dimensionless ratios (involving eleven flow parameters) which must be preserved.

Occasionally model tests have been carried out in which only the ratio of inertia and buoyancy forces is maintained constant [86, 89]. (That is, the Froude number is the same in model and full-size.) This involves scaling either the airspeed or the temperature used. If the temperature is scaled, errors due to heat losses by conduction or radiation may be introduced. The two series of tests mentioned (a  $\frac{1}{4}$ -scale test of a large occupied chamber with a forced ventilation system [86]—the problem being the uniform dissipation of heat from the occupants, and an investigation of fog dispersal [89] using 1/15, 1/20, 1/60 scale models) resulted in full size constructions which showed the model tests to be reasonably accurate.

Another approach was used by Rydberg [90]. He used brine as his fluid and produced density changes by altering the salt concentration. By these means he was able to investigate the air movements resulting from opening a window when there was a temperature difference between the air on either side of it. No modelling of heat transport other than by fluid motions was possible and although he investigated the possibility of salt diffusion representing heat transfer within the air he found it impractical.

#### IV:4. Analogue models, Scott [91].

These techniques depend on the construction of an analogy between characteristics of the ventilation and some other physical variable (such as electric circuit constants) which are more readily manipulated by the experimenter. Such analogies may be established via an explicit mathematical model for the ventilation processes, or by a direct correspondence between the two sets of variables (which implies that they may be described by the same mathematical model even though this may not be determined). The correspondence between analogue and actual phenomena is usually imperfect, but in some circumstances the similarities are great.

Mechanical ventilation via ducts has been electrically simulated [e.g. 91] but a naturally ventilated system of interconnecting rooms and corridors is not normally well represented by such a simple resistance network, because of the lower airspeeds and larger openings involved. The processes involved in thermally induced ventilation do not lend themselves to easy simulation.

An alternative approach would be to try to simulate the thermal conditions of a building and to find the necessary ventilation to produce results observed in the field. The accuracy of this method would depend on the accuracy of the simulation and of knowledge of the various heat flow paths.

## V. CONCLUSIONS

### V:1. Tracer techniques

V:1(a). There are two methods of using tracer gases to investigate natural ventilation which are of practical importance:

*The rate of decay method* requires relatively little time and equipment and gives a single result which is an estimate of the rate of change of air in the enclosure, assuming perfect mixing. The uncertainty of the method has been estimated as being up to  $\pm 15$  per cent in field conditions. Bias in the estimate is likely, but this is small compared to the random errors.

*The transfer index method* does not depend on assumptions about mixing. It yields a set of transfer indices between points showing the amount of air movement between them, from which it is possible to infer effective ventilation rates. The amount of information which may be produced about the detailed movement of air is large, but correspondingly, so is the effort (in terms of time and equipment and analysis of results) involved. The accuracies which can be achieved should be considerably better than those of the rate of decay method, but no detailed investigation has been published.

V:1(b). *The combination of gas and detector* with the least experimental drawbacks is helium measured with a katharometer. In the absence of flames or electric heating elements the combination of nitrous oxide measured by i.r. absorption is competitive, and has a wider range of detectable concentrations. Over long series of tests it is also more economical. However in these circumstances hydrogen, measured with a katharometer has all the advantages of the helium-katharometer combination with the additional attraction that, in the United Kingdom, hydrogen is much cheaper than helium.

### V:2. Air movement

V:2(a). *Airflow pattern determination*. Probably the best single method of finding the air circulation pattern is to use one of the various smoke tracers, as these more nearly follow vertical air movements. In large spaces, neutral buoyancy balloons are easier to trace.

V:2(b). *Low airspeed determination*. The lowest air motion detectable is 0.01 ft/s, this being possible with a low-speed hot-grid anemometer. This figure is for horizontal airflow, the limiting vertical motion detectable is unknown. If an instrument having less effect on the flow is required (the hot-grid instrument is about 1 in. square and includes flow straighteners) a hot-wire anemometer has been described [69] which is useable down to about 0.07 ft/s.

### V:3. Model techniques

V:3(a). *Wind induced ventilation*. With careful construction it is possible to use wind-tunnel models to determine external pressure distributions and

qualitative patterns of indoor air movement. Actual indoor airspeeds have nowhere been reliably estimated in models. There is no evidence for or against the use of models to predict ventilation rates due to wind action.

V:3(b). *Thermally induced ventilation.* There is insufficient evidence to establish whether thermally induced ventilation can be accurately determined by model studies.

V:3(c). *Analogue models.* No electrical simulation of actual ventilation has been published. The methods of simulating airflow in a system of ducts by a resistance network will not accurately represent natural ventilation.

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