VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

6th AIC Conference, September 16-19 1985, Netherlands

PAPER 27

Ventilation efficiency measurements in occupied mechanically ventilated buildings

D.J. Dickson

Electricity Council Research Centre, Capenhurst, Chester, CH1 6ES, England.

SYNOPSIS

The various meanings of ventilation efficiency are briefly summarised. The residual life time of a released tracer gas is chosen as the most meaningful and convenient basis for local efficiency measurements in large, occupied, mechanically ventilated buildings. Measurements were carried out in ten public swimming pool halls. Sulphur hexafluoride tracer gas was released from a 20 ml syringe at various locations around the pool hall and the integrated concentration with respect to time was measured at the exhaust air duct. This was extrapolated to infinite time using the measured decay rate. Hence the median residence time of the tracer after release was found and compared with the corresponding value for uniform and complete mixing using the measured exponential decay rate. The ratio of these two times was taken as a measure of the ventilation efficiency.

None of the ventilation systems tested proved significantly more efficient than the others overall. Local variations were however detected at individual sites and the method shows promise for application in occupied buildings, where minimum intrusion is required.

Symbols

A	fresh air change rate
C	contaminant or tracer concentration
q	volume of tracer gas
Q	rate of supply of fresh air
r	rate of supply of tracer
t	time
T	transfer index
Σ	ventilation efficiency
τ	median residence time

1. Introduction

The general purpose of ventilation is to supply 'fresh air' and to remove unwanted or harmful constituents from the local environment. The contamination may be released steadily or in discrete short bursts; alternatively there may be an existing contaminant of unknown history. However, in all cases the objective is to achieve as rapidly as possible, and maintain, an acceptably low concentration of contaminant in the occupied parts of the space. This means that not only must the ventilating air be 'uncontaminated' but also it must be delivered in such a way that the contamination is removed 'efficiently' to where it can do no harm.

It is not usually feasible to drive out the contamination before an advancing front of clean air (so-called piston flow) because intermixing of the old and new air is inevitable. However, this situation would represent the best possible ventilation and is most nearly approached by a local exhaust facility, such as a hood, which removes most of the contaminant before it has time to mix with the room air. Most often contamination is removed by dilution; fresh air is supplied, and stale air therefore removed, at a rate Q sufficient to maintain the local contaminant concentration C_j at point j below a specified maximum permissible value C_{max}. If the contaminant concentration C is uniform throughout the space then it will be removed at rate CQ and if the rate of supply is q the requirement for acceptable conditions is:

$$Q \geqslant \frac{q}{C_{max}}$$

This process is in some sense obviously less 'efficient' than the former situation, and it will take longer for the contaminant to be removed.

2. Background

The above brief description of the ventilation process suggests two approaches for defining and measuring 'ventilation efficiency': either in terms of concentrations or residence times. The rate of decay of an existing contaminant, or the equilibrium concentration for a continuous release, are both frequently used to measure ventilation rates in spaces where the air is well mixed. The usefulness of the measurement of local decay rates has been questioned by Sandberg[1] who shows that decay rates at different locations in a space are time dependent and no unique local air change rate can be defined. He suggests that the use of residence times is more meaningful, i.e. the time taken for the contaminant to be removed from the space.

A similar approach was adopted earlier by Lidwell[2] who introduced the idea of measuring the 'transfer index' between two points, defined as 'the integrated concentration at one point following the liberation of unit quantity of tracer at the other'. Thus if a quantity q of tracer is released at point P and the concentration C(t) is measured at point Q then the transfer index between P and Q is defined as

$$T = \frac{1}{q} \int_0^\infty C(t)\ dt.$$

T has the dimensions of time/volume and under complete mixing conditions T is the reciprocal of the air change rate as usually measured. Hence $\frac{1}{T}$ can be described as the 'equivalent ventilation'.

Sandberg[1] developed this idea further in terms of the 'age' of the air at a point, which is defined as the time that has elapsed since the air entered the room. This represents therefore the 'freshness' of the air at that point. Efficient ventilation at a chosen location is associated with a young age of the air there. Owing to the inevitable random fluctuations in air flow there will exist a distribution over time of ages which can be described by an average value at a point j given by

$$\frac{\int_0^\infty C_j\ (t)\ t\ dt}{\int_0^\infty C_j\ (t)\ \ dt} \qquad (1)$$

In the context of contaminant removal it is convenient to think of the fate of a contaminant or tracer released at the point of interest. The time taken for the contaminant to leave the space has been called the 'residual life time'[3]. The internal age distribution and the residual life time distribution have been shown by Sandberg to be identical.

3. Ventilation efficiency

In an occupied mechanically ventilated building it is convenient to release a tracer gas at a chosen location and measure the integrated concentration versus time at the exhaust terminal or duct. The ventilation efficiency at the place where the tracer was released can then be defined in terms of a measured mean residual life time.

Imagine tracer gas to be released as a short burst at the chosen location. If the ventilation is efficient then the tracer will be rapidly removed and will soon appear at the exhaust terminal. If on the other hand the local ventilation is poor, the tracer will linger around the location where it was released and will take a longer time to reach the exhaust terminal. Thus if the tracer concentration is recorded versus time at the exhaust terminal the results, for a pulse released at time zero, would be as indicated in Figure 1.

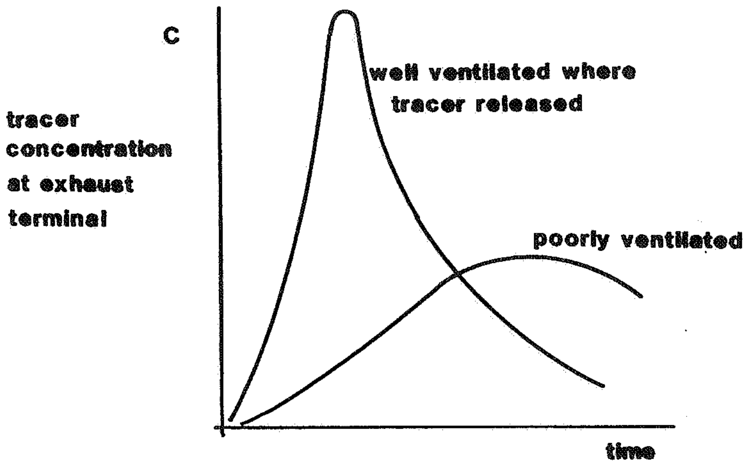


Figure 1 Tracer gas concentration at the exhaust terminal following release of a short burst of tracer at time = 0

The integrated area under the curves $\int_0^\infty Cdt$ will be the same in both cases since eventually all the tracer will pass the exhaust terminal, unless air leakage occurs other than through the ventilation system. If $\int_0^t Cdt$ is plotted against t then the result will be as shown in Figure 2 where in a well ventilated situation a rapid rise of $\int_0^t Cdt$ occurs soon reaching the maximum value equal to $\int_0^\infty Cdt$.

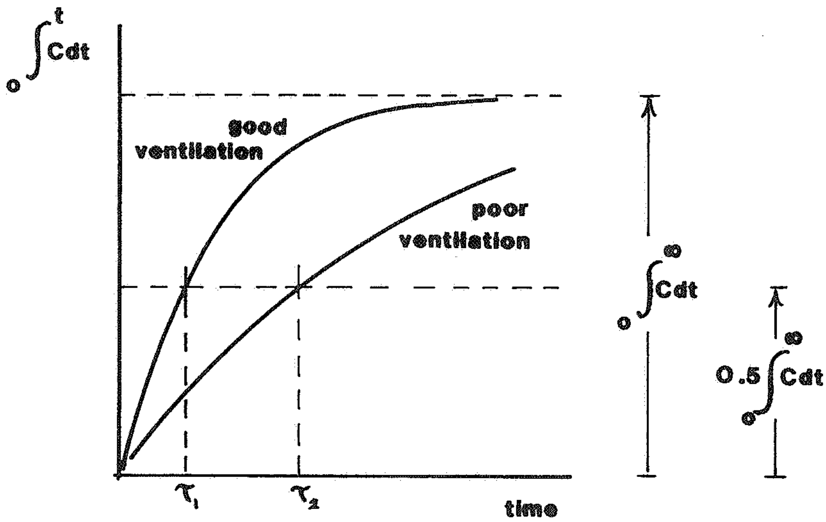


Figure 2 Integrated concentration versus time at the exhaust terminal following release of a short burst of tracer at a chosen location at time = 0

Rather than using expression (1) to find the average residence time of the tracer in the space it is more convenient, following Danckwerts[4], to use the median age τ which is the time taken for half the tracer to reach the exhaust terminal. τ is simply the value of t for which

$$\int_0^t Cdt = \frac{1}{2} \int_0^\infty Cdt$$

see Figure 2.

The ventilation efficiency can then be defined by comparing this measured median residence time τ_s with the residence time which would occur if the air in the space was completely and uniformly mixed τ_x. For uniform mixing the tracer concentration would decay exponentially according to

$$C_t = C_o e^{-At} \qquad (2)$$

where C_t = concentration of tracer at time t
C_o = concentration of tracer at time 0
A = air change rate per unit time

From equation (2)

$$\int_0^\infty Cdt = \frac{C_o}{A}$$

where C_o is the initial tracer concentration which would exist if instantaneous complete mixing took place = (volume of tracer released/room volume). The value of t for $\int_0^t Cdt = \frac{1}{2} C_o/A$ can be shown to be given by $e^{-At} = 0.5$. The median life time for a released contaminant under fully mixed conditions is therefore $\tau_x = 0.693/A$. If the measured median life time is τ_s then the ventilation efficiency, equivalent to Sandberg's relative air diffusion efficiency[3] is

$$\varepsilon = \frac{\tau_x}{\tau_s}$$

If $\tau_x = \tau_m$ then $\varepsilon = 1$ representing the rapid complete mixing situation. In a stagnant region $\tau_s > \tau_x$ and $\varepsilon < 1$. Similarly values of $\varepsilon > 1$ imply removal of contaminants more effectively than for uniform mixing i.e. an amount of piston flow behaviour.

4. Experimental method

All the buildings of interest were mechanically ventilated. A short burst of tracer gas was released at various places in turn and the concentration measured as a function of time at the exhaust terminal or duct.

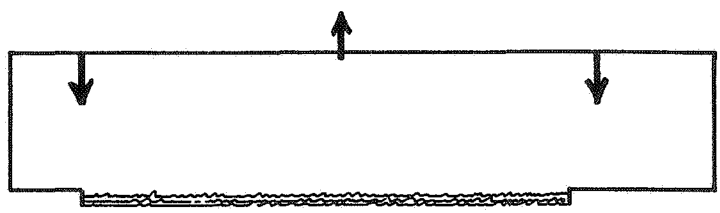
Sulphur hexafluoride was convenient as a tracer gas because it is harmless and equipment capable of measuring concentration of 10^{-9} is readily available, and therefore requiring only 10 ml of tracer gas in a 10,000 metre^3 building. At a pre-arranged signal a measured volume of gas (usually 20 ml) was released at the place of interest from a syringe. The syringe was filled by its hypodermic needle by withdrawing gas through a septum on the gas bottle stored outside and downwind of the building. The gas analyser (AI Model 505, SF_6 Detector Chromatograph) was situated usually in the plant room at a convenient place for sampling to take place in the exhaust duct through a suitable existing inspection hole. Output from the analyser used in the sample mode is a series of pulses which were recorded on a strip chart recorder and analysed manually. Sampling interval was 1.5 to 2 minutes.

5. The buildings

As part of a larger survey, measurements were carried out in 10 public swimming pools.

The pool halls were all mechanically ventilated at an air change rate of about 4 air changes per hour although in many of the pools recycling of the air to conserve energy reduced the fresh air change rate to 1 or 2 air changes/hour.

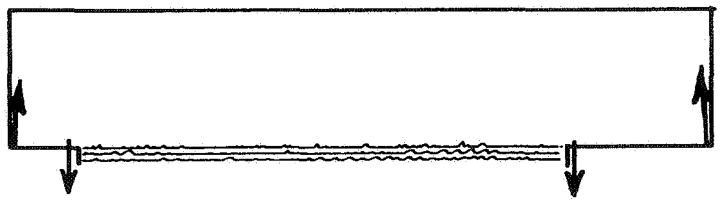
The air distribution systems were mainly of two types. The most common arrangement (6) was for air to be supplied more or less vertically downwards along the perimeter of the pool, with return air grilles also in the ceiling over the centre of the pool. Figure 3 shows this schematically and lists the dimensions of pools of this type.



Pool Code	l x b h (metres)	Volume (m^3)
A	39.7 x 18.5 x 3.6	2650
B	32.7 x 18.3 x 5.7	3070
C	28.7 x 24.6 x 7	5300
D	42 x 24 x 7.2	6500
E	51.2 x 23.3 x 8.9	12070
F	49.7 x 31.7 x 9.1	14000

Figure 3 Pools with ceiling mounted supply and extract positions

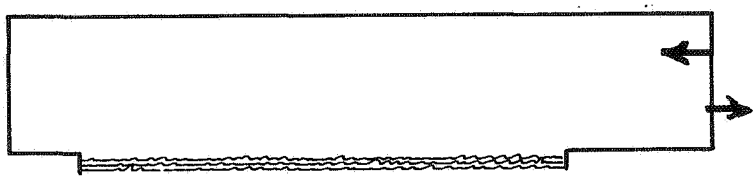
Some more recently built pools (3) have air supply slots in the floor adjacent to the perimeter walls so that the air is directed vertically upwards. The air return is combined with the pool water overflow grid at the pool side. These are all level deck pools. Figure 4 illustrates this type.



Pool Code	l x b x h (metres)	Volume (m^3)
G	30.5 x 17 x 5.5	2850
H	34.2 x 14.4 x 6	2950
I	32.4 x 22.8 x 6	4350

Figure 4 Pools with floor mounted supply and extract positions

One of the pools had cross flow ventilation with air supplied horizontally at high level with the return air grille on the same side wall at low level, Figure 5.



Pool Code	l x b x h (metres)	Volume (m^3)
K	30 x 17 x 3.4	1770

Figure 5 Cross flow ventilated pool

Since the time available at each pool was limited to a few days, a definitive study of the advantages and performance of each system was not possible. The aim was to show the feasibility, and assess the practicalities of this assessment method.

In all cases there was no difficulty in placing the gas sampling tube in the return air duct. The SF_6 tracer (20 ml) was released from a syringe (needle removed) usually near the water level. The time of release was notified to the plant room via a two-way radio and marked on the chart. The time of tracer release was denoted zero time; the duration of release was at most a few seconds which is negligible on the time scale of measurement which was tens of minutes.

Typical response curves are shown in Figure 6.

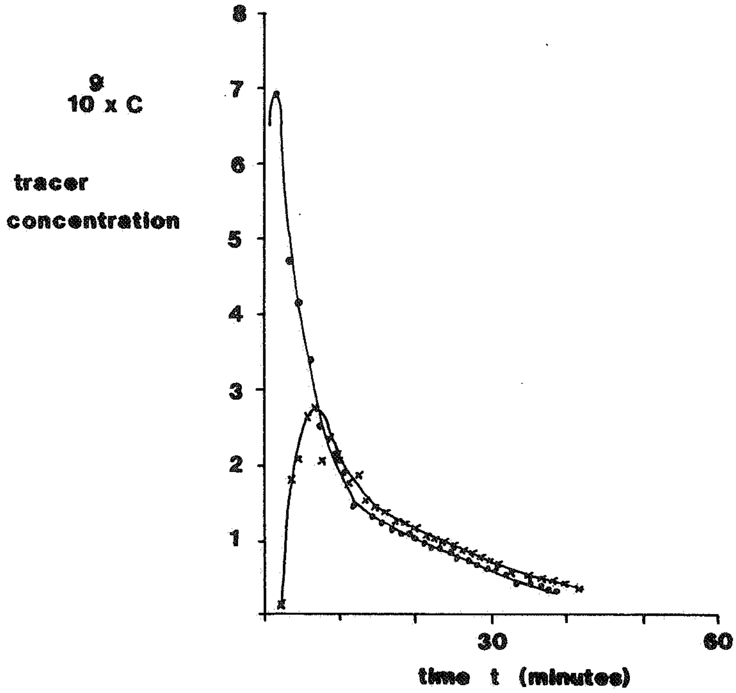


Figure 6 Measured concentration in extract duct for tracer released at pool side at time t = 0

A simple trapezium rule calculation on a programmable calculator enabled computation of $\int_0^t Cdt$ in each case, Figure 7.

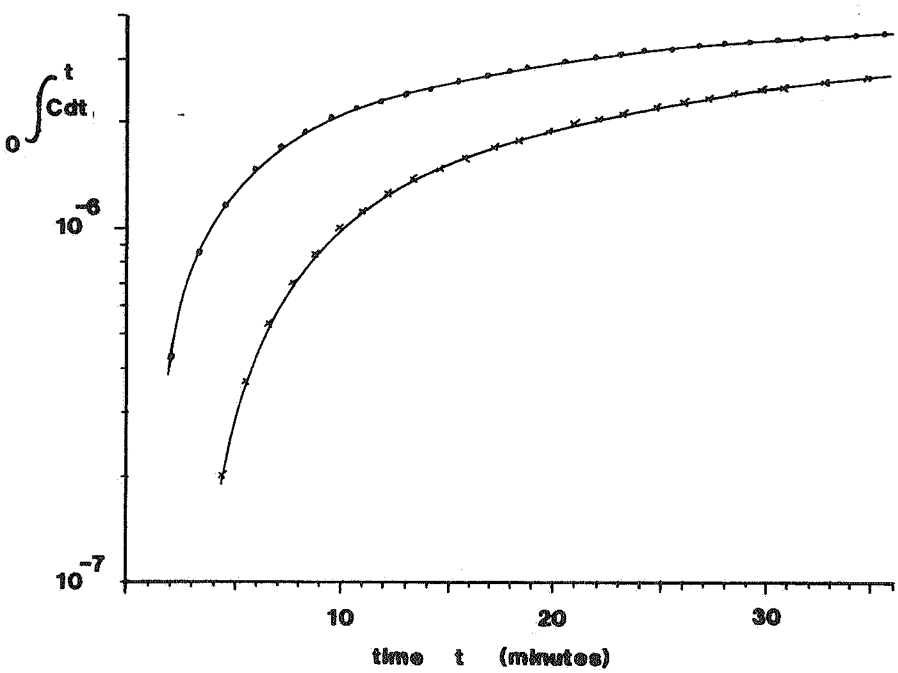


Figure 7 Integrated concentration versus time at extract duct

The time when measurements stopped t_m was typically after 30 to 60 minutes.

From the decay part of the tracer in Figure 6 on a plot of logarithm (concentration) versus time the decay rate before time t_m can be found, hence assuming that the same exponential decay rate persists until all the tracer is removed it is possible to calculate $\int_{tm}^{\tau} Cdt$ thus:

Let $C_t = C_o\ e^{-At}$ represent the exponential decay process then

$$\int_{tm}^{\infty} C_o e^{-At} = \frac{C_o}{-A} \left[e^{-At}\right]_{tm}^{\infty} = \frac{C_o e^{At_m}}{A} = \frac{C_m}{A}$$

where C_m is the tracer concentration at time t_m.

By adding these calculated values to the measured value of $\int_{o}^{tm} Cdt$ the values of $\int_{o}^{\infty} Cdt$ were obtained.

The median residence time is then $\frac{1}{2} \int_{o}^{\infty} Cdt$.

If the decay rate as measured in the latter part of each test is assumed to represent the actual mean fresh air ventilation rate in the space then this can be used as a basis for the fully mixed performance and τ_x is given by the value of t for which

$$\int_{o}^{t} Cdt = \frac{1}{2} \int_{o}^{\infty} Cdt$$

$$\text{if } C = C_o\ e^{-At}$$

i.e. $e^{-At} = \frac{1}{2}$

i.e. $\tau_x = \dfrac{0.693}{A}$

The value of the measured median residence time τ_s is obtained from Figure 7.

6. Results

In comparing one mechanically ventilated space with another the most significant factor, in the absence of local extract, is the actual fresh air ventilation rate, i.e. τ_s correlated well with τ_x, Figure 8. Actual values of median residence time were in the range 10 to 60 minutes.

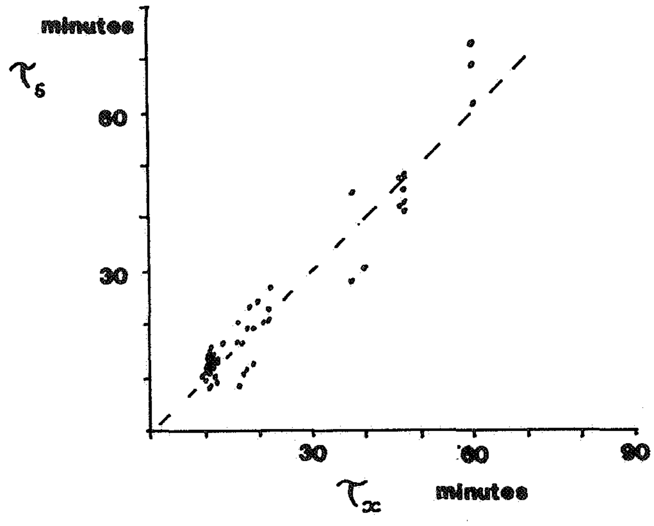


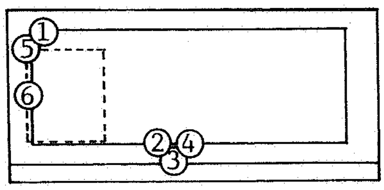
Figure 8 Measured τ_s and fully mixed τ_x residence times

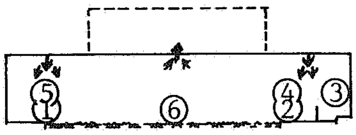
Within each pool hall the value of $\Sigma = \tau_x/\tau_s$ was found at various locations around the pool, mostly near the water level. The results are given in Table 1 and summarised in Figure 9.

Variations in ε were found in the region 0.75 to nearly 2. No definite pattern emerged and no system proved significantly more efficient than any other. Poor local ventilation tends to occur at central locations over the water and in the shelter of balconies. Better than average efficiency occurred very close to extracts on level deck pools where the air return and water overflow are combined.

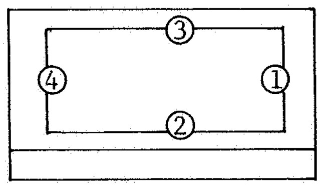
Table 1 Results of ventilation efficiency measurements in ten public swimming pool halls

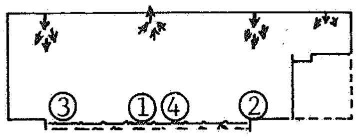
Pool Code	τ_x	τ_s (minutes)	τ_x/τ_s
A 1	10.6	11.5	0.92
2	10.2	10.2	1.00
3	11.1	10.3	1.08
4	10.0	9.5	1.05
5	10.0	10.3	0.97
6	10.2	11.7	0.87



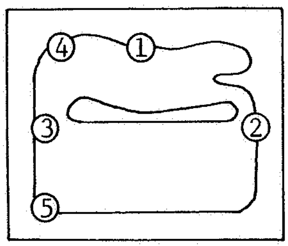


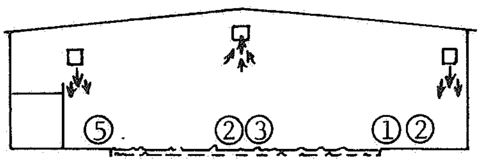
Pool Code	τ_x	τ_s (minutes)	τ_x/τ_s
B 1	13.6	16.4	0.83
2	11.2	14.4	0.78
3	11.1	8.4	1.32
4	12.2	9.7	1.26



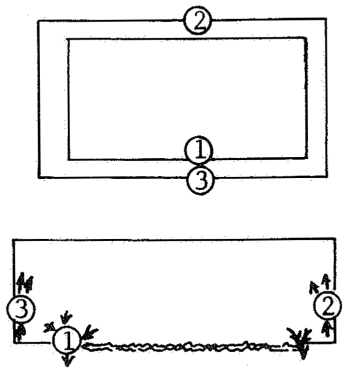


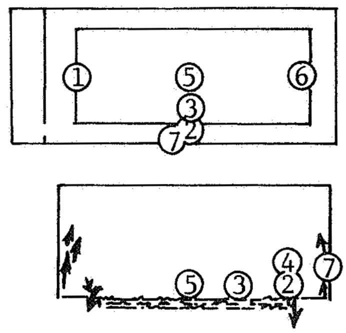
Pool Code	τ_x	τ_s (minutes)	τ_x/τ_s
C 1	11.6	13.0	0.89
2	12.1	13.5	0.89
3	10.9	12.0	0.91
4	11.8	9.5	1.24
5	11.1	12.0	0.93

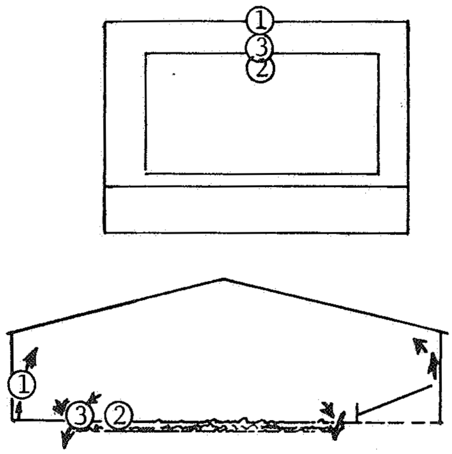


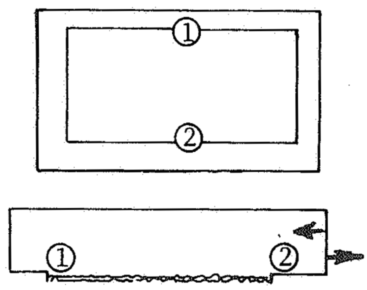


Pool Code	τ_x (minutes)	τ_s	τ_x/τ_s
G 1	16.5	8.5	1.94
2	16.1	17.0	0.95
3	16.4	16.5	0.99
H 1	16.2	20.5	0.79
2	17.8	11.2	1.60
3	18.2	19.5	0.93
4	19.8	24.5	0.81
5	21.9	21.0	1.04
6	18.9	19.5	0.97
7	18.1	24.0	0.75
I 1	60	62	0.97
2	60	73	0.82
3	60	69	0.87
K 1	22.0	23	0.96
2	22.6	27	0.84

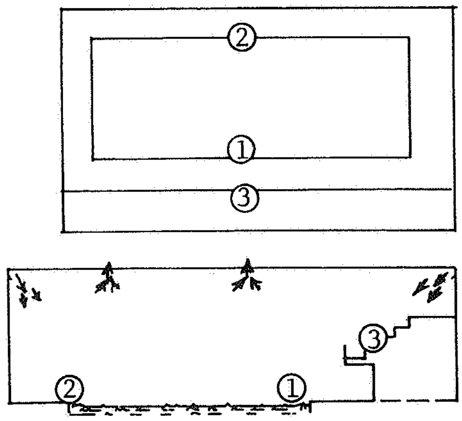


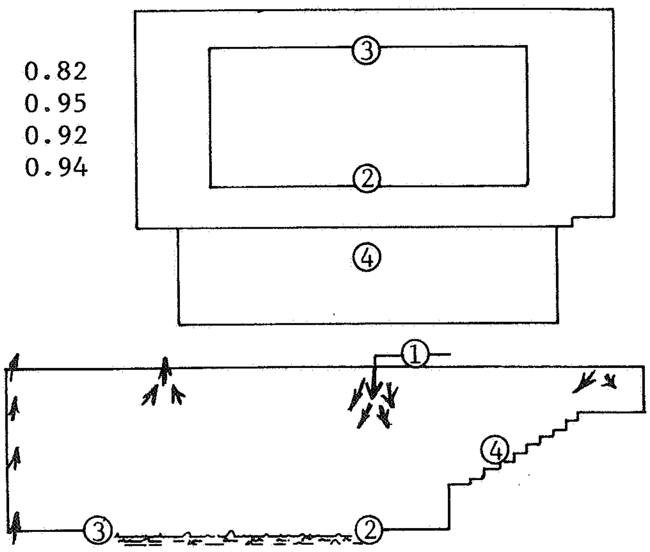


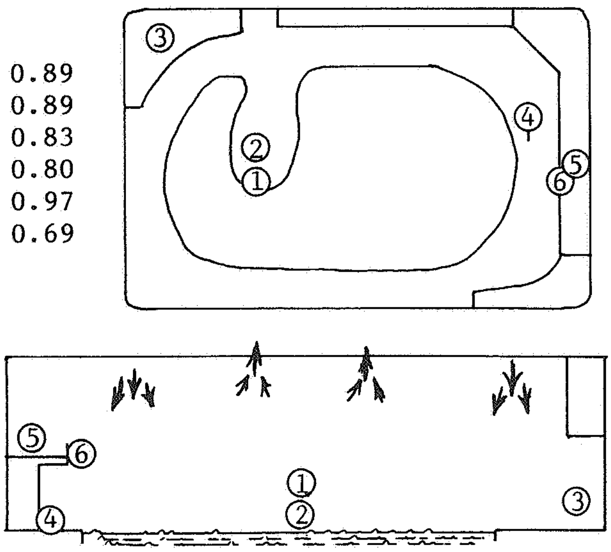




Pool Code	τ_x (minutes)	τ_s (minutes)	τ_x/τ_s
D 1	37.8	28.5	1.33
2	40.0	41.0	0.98
3	37.8	45.0	0.84
E 1	21.0	25.5	0.82
2	21.5	21.5	0.95
3	21.7	23.5	0.92
4	18.8	20.0	0.94
F 1	10.7	12.0	0.89
2	10.7	12.0	0.89
3	10.7	12.9	0.83
4	11.6	14.5	0.80
5	11.2	11.5	0.97
6	10.7	15.5	0.69







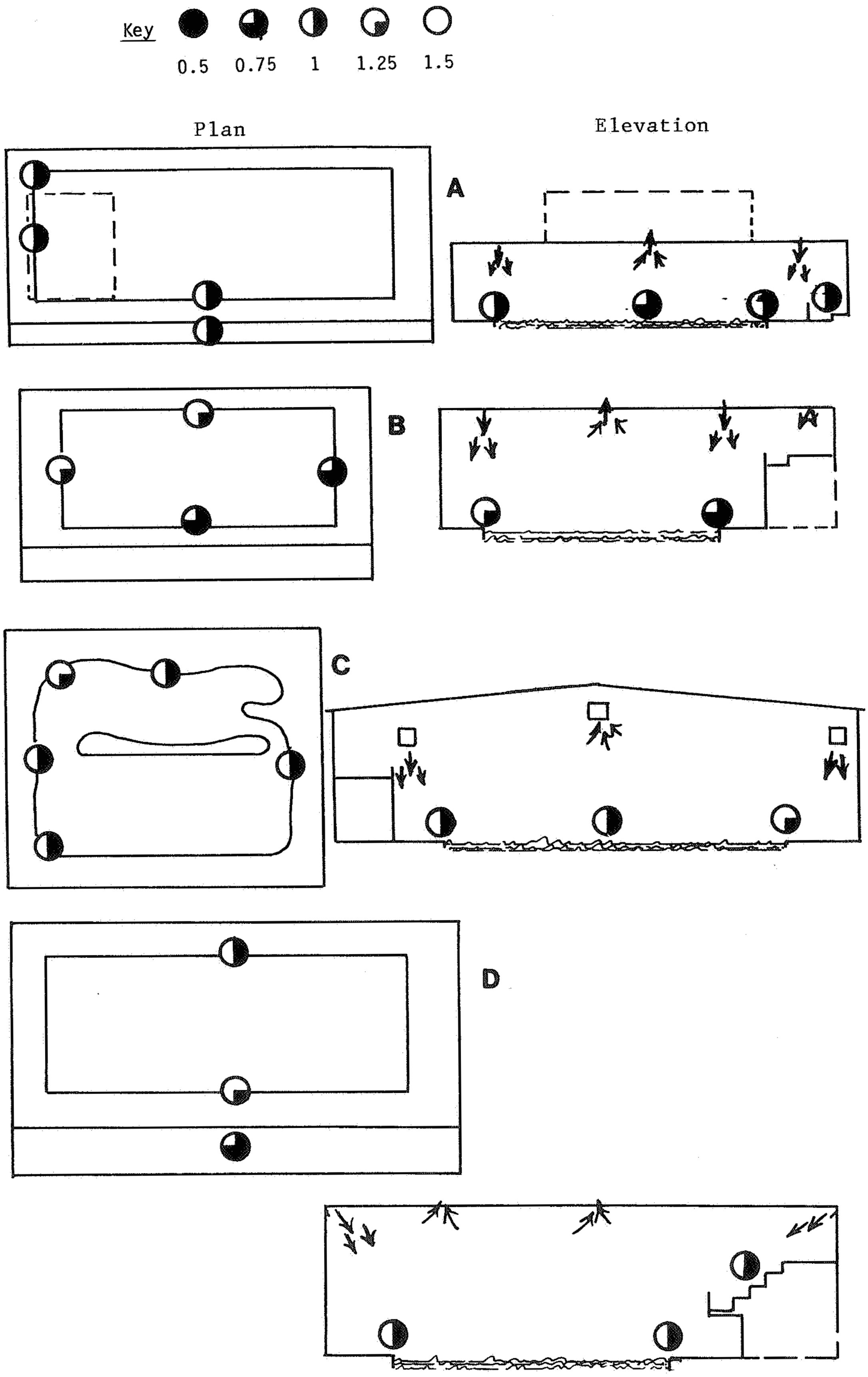


Figure 9 Measured values of τ_x/τ_s

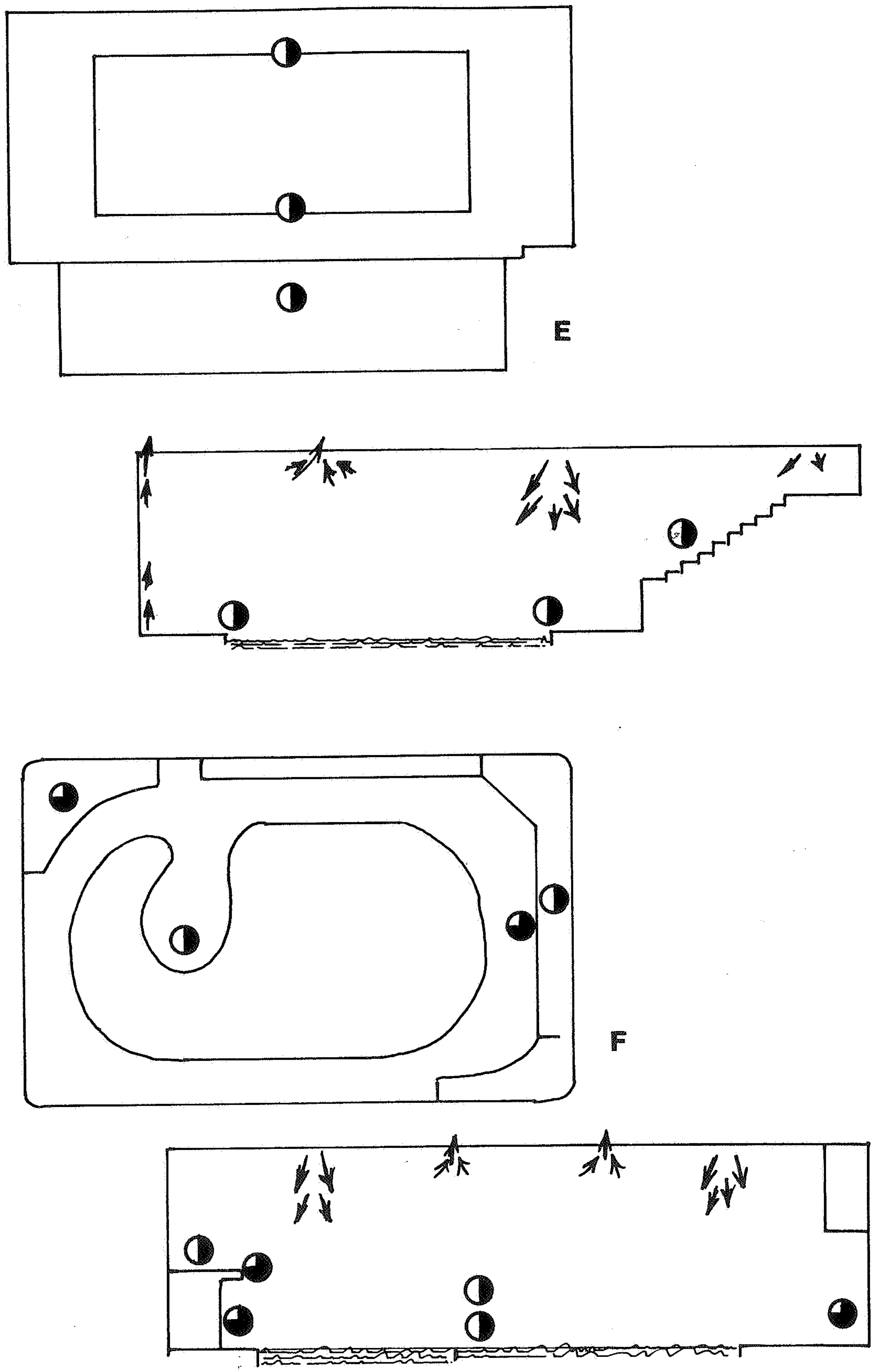


Figure 9 continued

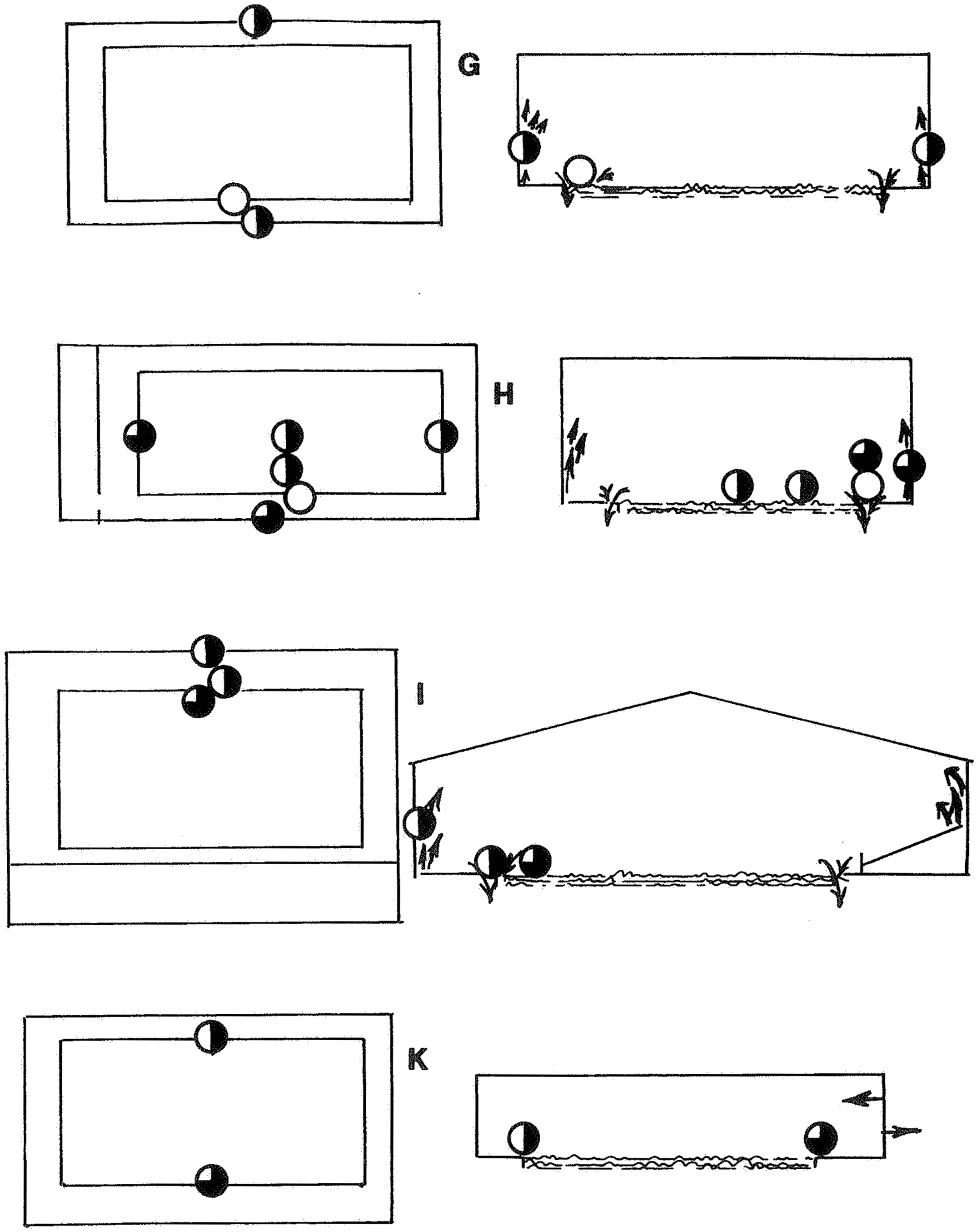


Figure 9 continued

7. Conclusions

The 'ventilation efficiency' can be defined in terms of contaminant residence times.

Measurements are possible in occupied mechanically ventilated buildings without interfering with the normal usage patterns.

Conditions in mechanically ventilated swimming pool halls are consistent with the existence of good mixing.

8. Acknowledgements

The co-operation of the pool staff and Local Authorities is gratefully acknowledged.

9. References

[1] Sandberg, M. Building and Environment, 16 (2), 1981, pp 123-135.

[2] Lidwell, O.M. J. Hyg. 58 (3), 1960, pp 297-305.

[3] Sandberg, M. & M. Sjoberg. Building and Environment, 18 (4), 1983, pp 181-197.

[4] Danckwerts, P.V. Chem. Eng. Sci. 9, 1958, pp 78-79.