# AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS

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THE MEASUREMENT OF AIR INFILTRATION RATES IN LARGE ENCLOSURES AND BUILDINGS

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## SYNOPSIS

The paper describes work carried out as part of a research contract funded by the U.K. Department of the Environment and the Commission of the European Communities.

The object of the research is to develop a validated method of measuring air infiltration rates in industrial buildings and to use the method to measure ventilation rates in some selected buildings.

The following points are discussed:

- (a) Poor mixing in industrial buildings. Implications of poor mixing for choice of measurement method and interpretation of results.
- (b) Review of possible measurement methods. Trials of a low cost fuel cell gas analyser designed for measuring ethanol vapour.
- (c) A computer-controlled multi-point tracer gas concentration measurement system using infra-red gas analysers and introus oxide as the tracer gas.
- (d) Preliminary results obtained with only natural ventilation.
- (e) Need to validate method by comparing ventilation rates measured by tracer gas method with mechanical extract or supply rates while depressurising or pressurising a test enclosure. Airtightness testing of two industrial buildings in preparation for validation work.

# LIST OF SYMBOLS

Definition	Units
Tracer gas concentration	Dimensionless (%, parts per million,etc.)
Tracer gas concentration in zone z	Dimensionless
Error in calculated time-integrated ventilation rate	m <sup>3</sup>
Air flow rate	m <sup>3</sup> /s
Air flow rate from zone x to zone y, > = 0	m <sup>3</sup> /s
Zone O is defined as the outside atmosphere.	
Time	S
Volume	m <sup>3</sup>
Volume of zone z	m <sup>3</sup>
	Definition Tracer gas concentration Tracer gas concentration in zone z Error in calculated time-integrated ventilation rate Air flow rate Air flow rate from zone x to zone y, > = 0 Zone 0 is defined as the outside atmosphere. Time Volume Volume of zone z

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The floor area of industrial and warehouse buildings in the UK is about  $410,000,000 \text{ m}^2$ .

If we assume that:

- i) the mean storey height is 6m
- ii) the inside temperature is maintained at 15.5°C
- iii) the ventilation rate is constant at one air change per hour
- iv) the number of degree days in the heating season (September ~ May) is 2200,

then the heat required to heat the air from ambient to inside temperature is 1.6 x  $10^{17}$  J/year. This represents about 3% of the total UK energy consumption by final users (5.8 x  $10^{18}$  J/year).

However, industrial and warehouse buildings usually consist of a single large space or a small number of large spaces. There is at present no reliable method of measuring ventilation rates in these spaces. Therefore, there is no way of knowing whether the energy loss and possible savings estimated above are over or under estimated and no certain way of determining the cost effectiveness of any measures taken to reduce unwanted ventilation.

The purpose of this research is to develop a method of measuring ventilation rates in large single cell buildings. This will allow data on ventilation rates to be collected and the effectiveness of measures for reducing ventilation rates to be assessed and thus enable energy conservation efforts to be directed to where they will have most effect.

# 2. VENTILATION RATE MEASUREMENT USING TRACER GAS

### 2.1 General Principles

The classical method of measuring ventilation rates is to inject a gas, known as a tracer gas, into the air in the building so as to differentiate it from the outside air. If the tracer gas injection strategy and concentration history are known, then it should in principle be possible to calculate the ventilation rate. Other methods of measuring ventilation rates are possible. For instance, if the total and conduction heat losses of a building were accurately known, the ventilation rate could be derived from the residual heat loss and the inside and outside temperatures. Such unconventional methods have been rejected for this research as containing too many uncertainties to allow their application at present to large buildings.

# 2.2 Perfect Mixing

It has been usual, when measuring ventilation rates using tracer gas methods, to assume that the air in the space is well mixed. This has been found to be a reasonable assumption for the small spaces such as dwellings and cellular offices where most previous measurements have been made. If there has been doubt that the air in the space is sufficiently well mixed, fans have been used to provide good mixing artifically.

If the air in a space is well mixed the concentration of tracer gas will be substantially constant throughout and the equations relating the ventilation rate and tracer gas concentration can be easily derived. Kronvall (9) derives the equations for the three common measurement methods, which are the concentration decay, constant concentration and constant emission methods. Tracer gas concentration only needs to be measured at one point in the space.

## 2.3 Imperfect Mixing

If the air in a space is not well mixed then the rate at which tracer gas is removed from the space will depend on the sum of the air flows out of the space and the tracer gas concentration in each air flow.

A single point concentration measurement will therefore not yield sufficient information to enable the ventilation rate to be calculated (or, in the case of the constant concentration method, to enable the tracer concentration to be controlled).

Ideally, each outward air flow would be identified and the appropriate tracer gas concentration measured. In practice, a multi-point tracer concentration measurement system would be used and the ventilation rate would be estimated from the information available.

#### 2.4 Simulation of Imperfect Mixing

To obtain an idea of what the consequences of imperfect mixing might be for ventilation rate measurements in a large space, a simple numerical model was developed which simulates a ventilation rate measurement by the concentration decay method.

The model has nine inside zones and one outside zone. Each zone is assumed to be fully mixed. The size of each zone, the initial tracer gas concentration in each zone and air flows in each direction between adjacent zones can be individually specified. The tracer gas concentration in the outside zone is always zero.

Considering first the case of a concentration decay measurement in a well mixed space, the equation relating the tracer gas concentration and time is

 $\ln C_{t2} = \ln C_{t1} - \frac{0}{V}$  (t2 - t1)

where  $C_{t1}$  = tracer gas concentration at time tl

 $C_{\pm 2}$  = tracer gas concentration at time t2

This is the equation of a straight line with gradient  $\frac{Q}{V}$  on a graph of lnC against t. The results produced by the the model were therefore plotted as a graph of lnC against t.

Exploratory calculations using this model produced the following results:

- i) All lines parallel, slope shallower than -Q.
- ii) Not all lines parallel, some slopes steeper and some shallower than -Q

V

iii) Not all lines parallel, all steeper than -Q.  $\overline{v}$ 

Examples of these are shown in Figures 1 - 3. The air flows assumed to produce these results are shown in Figures 4 - 6. Concentrations for zones 3,6 and 9 are not shown as they are the same as concentrations in zones 1, 4 and 7 respectively.

It will be noticed that the slope of the mean concentration line is in general not equal to the slope of the perfect mixing line, so any measurement method which simply relied on average tracer gas concentrations could be seriously in error if used in an imperfectly mixed space.

The range of tracer gas concentration needed to obtain straight concentration decay lines is sometimes very large, several decades. This is larger than the range of most practical instruments. If mixing in practice is as poor as has been assumed for these simulations, this problem will have to be dealt with by using a very large initial tracer gas concentration so as to observe the straight parts of the concentration decay curves as they pass through the instrument's measuring range, or by using an analysis technique which does not depend on exponential decay of tracer gas concentrations. Such a method is described in section 2.5.

The other possible results have not yet been produced, but there does not seem to be any reason why air movement patterns which will produce them should not be found. They are:

i) all lines parallel, slope steeper than -Q ii) all lines parallel, slope equal to -Q v iii) not all lines parallel, all slopes shallower than -Q

The model can be extended to a very large number of zones. The number used is limited mainly by the labour involved in developing the program and specifying the input data.

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#### 2.5 Analysis Method for Imperfect Mixing

This method is adapted from that described by Penman and Rashid (8). Figure 7 shows a generalised multi-zone model of ventilation of a space and air movement within it. It is assumed that the space can be divided into a number of wellmixed zones of known shape and size.

The general equation governing the tracer gas concentrations within the space is:

Rate of supply of gas - Rate of removal of gas = Rate of change of quantity of gas in space

The easiest ventilation rate measurement method to use is the concentration decay method, in which:

Rate of supply of gas = 0

The rate of removal of gas from the space is simply the sum of the air flow rates from each zone to the outside, each multiplied by its appropriate tracer gas concentration:

$$\sum_{z=1}^{Q_{10}} c_1 + Q_{20} c_2 + \dots + Q_{Z0} c_z$$

$$= \sum_{z=1}^{Z} Q_{z0} c_z$$

The rate of change of the quantity of tracer gas in the space is the sum of the volumes of the zones each multiplied by the appropriate rate of change of tracer gas concentration:

$$V \frac{1}{dt} \frac{dC_1}{dt} + V_2 \frac{dC_2}{dt} + \dots + V_Z \frac{dC_Z}{dt}$$
$$= \sum_{z=1}^{Z} V_z \frac{dC_z}{dt}$$

Thus

$$0 - \sum_{z=1}^{L} Q_{z0} C_z = \sum_{z=1}^{L} V_z \frac{dC_z}{dt}$$

During a concentration decay measurement the values of  $C_z$  and  $\frac{dC_z}{dt}$  will vary with time, so by integrating from time t0 to time

tl the following is derived:

$$-\sum_{\substack{z=1\\z=1}}^{Z} (Q_z \int_{to}^{C_z} dt) = \sum_{\substack{z=1\\z=1}}^{Z} (V_z (C_{z,t1} - C_{z,t0}))$$

In this equation  $\rm Q_{Z\,O}$  are unknown (assumed constant),  $\rm C_{Z}$  are measured and  $\rm V_{Z}$  are estimated.

By integrating over T time intervals the following set of simultaneous equations is obtained:

$$-\sum_{z=1}^{Z} (Q_{z0} \int_{t0}^{t1} C_{z}^{dt} dt) = \sum_{z=1}^{Z} (V_{z} (C_{z,t1} - C_{z,t0}))$$

$$-\sum_{z=1}^{Z} (Q_{z0} \int_{t1}^{t2} C_{z}^{dt} dt) = \sum_{z=1}^{Z} (V_{z} (C_{z,t2} - C_{z,t1}))$$

$$-\sum_{z=1}^{Z} (Q_{z0} \int_{t(z_{z}^{dt})}^{tT} e^{tC_{z}^{dt}} dt) = \sum_{z=1}^{Z} (V_{z} (C_{z,t1} - C_{z,t(T-1)}))$$

If T, the number of equations, equals Z, the number of zones within the space, then a unique solution for the  $Q_{zo}$  terms exists provided that all the equations are independent. However, experimental errors in measuring  $C_z$  and in estimating  $V_z$  make an alternative approach more interesting.

This alternative approach is to insert estimated values of  $\rm Q_{ZO}$  in the equations and rewrite them as:

$$\sum_{z=1}^{Z} V_{z}(C_{z,t1} - C_{z,t0}) + Q_{z0} \int_{t0}^{t1} C_{z}dt = E_{1}$$
  
to  
$$\sum_{z=1}^{Z} V_{z}(C_{z,t2} - C_{z,t1}) + Q_{z0} \int_{etc.t1}^{t2} C_{z}dt = E_{2}$$
  
$$\sum_{z=1}^{Z} V_{z}(C_{z,t1} - C_{z,t(T-1)}) + Q_{z0} \int_{c_{z}}^{tT} C_{z}dt = E_{T}$$

Here the magnitude of each E represents the magnitude of the discrepancy between the observed values of  $C_z$  and the assumed values of  $Q_{ZO}$ .

Provided that T > Z and that the equations are sufficiently independent, it should be possible to use iterative techniques to find the values of the  $Q_{ZO}$  terms which minimise an error function:

$$f(E_1, E_2, ..., E_T)$$

subject to the constraint that

$$Q_{zo} > = 0$$

for all z.

The assumption that the space can be divided into a number of well-mixed zones of known shape and size is a very great simplification of the true situation.

Section 7 outlines a programme of work intended to provide data on the accuracy of the method.

# 3. MIXING IN LARGE SINGLE CELL BUILDINGS

#### 3.1 Probability of Imperfect Mixing

A preliminary analysis suggests that imperfect mixing is likely in large single cell buildings. These are typically factories or warehouses. They often contain large quantities of goods or machinery which present barriers to air circulation between different parts of the space. They are often heated by heaters mounted at high level, which can create stable layers of warm air at the top of the building and cool air below with little mixing between them. This suggests that imperfect mixing is likely to be a problem. A search has been carried out to obtain information on air movement in naturally ventilated large buildings, but very little published work has been found. Imperfect mixing, however, seems to be common (1, 2, 7).

Air movement in buildings with mechanical supply ventilation or forced warm air heating is largely determined by the mechanical systems when these are in operation. The effectiveness of mechanical systems in mixing tracer gas within a room is currently being studied by other researchers (3, 4,5, 6).

# 3.2 Objections to Artificial Mixing

There are both theoretical and practical objections to using fans to obtain good mixing in an imperfectly mixed large space.

The theoretical objection to the use of mixing fans is that they may change the infiltration rate by, for instance, destroying temperature gradients within the building.

The practical objections are that:

- i) in a large building, large and expensive mixing fans are likely to be required.
- in an occupied building, the installation of mixing fans will probably be time consuming for the research team and inconvenient for the occupants.

The programme of research is therefore based on the premises that imperfect mixing is likely and that the ventilation rate measurement method should take account of this. This means that a multi-point tracer gas concentration measurement system will be required.

#### 4. POSSIBLE NOVEL INSTRUMENTS

#### 4.1 Disadvantages of Conventional Instruments

Conventional instruments for measuring tracer gas concentrations, such as infra-red gas analysers or electron capture detectors, suffer from certain disadvantages when a large number of measurement points are required. The instruments tend to be rather bulky and heavy, which is a disadvantage when working away from the laboratory. Also, a balance has to be struck between using many analysers, which is expensive, and using a smaller number of analysers each serving a larger number of measurement points, which results in each measurement point being served less frequently. A survey of available instruments was therefore made in order to discover whether recent advances in technology had resulted in possible new methods of tracer gas measurement.

# 4.2 Novel Instruments

The following tracer concentration measurement methods were found to be of interest:

- (a) absorption of infra-red laser beam
- (b) collection of tracer(s) in thermal desorption tubes
- (c) detection of ethanol by use of fuel cells.

#### 4.2.1 Absorption of Infra-red Laser Beam

This method is based on the absorption of an infra-red laser beam as it passes through the test space. The beam is tuned to an absorption frequency of the tracer gas, and the decrease in the intensity of the beam from the transmitter to the receiver indicates the quantity of tracer gas along the path of the beam.

This method can be applied in various ways. The transmitter and receiver can be separate, or they can be adjacent and the beam can be reflected from a room surface so as to fall on the receiver. The measurement beam can be used alone, or together with a reference beam at a slightly different frequency, which will provide a continuous indication of the effects of absorption due to other causes than the tracer gas. The essentials of the method are shown in figure 8.

The disadvantages of this method are the high cost of the equipment  $(\pounds40 - 50,000)$  and that it is essentially an averaging method. It can cover a great deal of space from a single point, but yields insufficient information about the distribution of tracer gas in the space. It was therefore rejected as unsuitable.

# 4.2.2 Collection of Tracer(s) in Thermal Desorption Tubes

The basic measurement equipment consists of a small, relatively inexpensive adsorption tube of similar dimensions to a ball point pen. The tube is packed with a suitable adsorption media eg "chromosorb" which is used to adsorb samples either by direct diffusion, or alternatively a controlled air flow may be induced by the use of a pump. After exposure, a storage cap is placed over the tube for transportation to the laboratory for analysis. Analysis of the sample tubes may be carried out remotely from the test site, using an automatic gas analyser. The complete sampling tube is heated to 250°C in a flow of carrier gas and the vapours transported directly to the gas chromatograph column. This procedure both injects the sample, and cleans the adsorption tube, which may then be capped and stored for re-use.

A practical ventilation rate measurement system (shown in figure 9) consists of a large number of adsorption tubes divided into groups, one group for each measurement point. A small sampling tube runs from each measurement point to each group of adsorption tubes, where it divides to form a manifold connected to their inlets. The outlets of the adsorption tubes are connected to a common vacuum pump. Valves control which adsorption tube in each group is in use.

Such a system has the advantage that it could be used with multiple tracers to obtain detailed information about air movements. It has the following disadvantages:

- (a) no information is available to the experimenters while performing the measurements
- (b) as a consequence of (a), the system is unable to be used for constant concentration measurements
- (c) the number of adsorption tubes and valves and the size of the racks required to contain them increases in proportion to the number of times a concentration is required for each measurement point.

The system was therefore rejected as unsuitable.

#### 4.2.3 Detection of Ethanol by use of Fuel Cells

#### 4.2.3.1 General

The possibility of using fuel cells as a primary source of energy by converting chemical energy directly into electrical energy has been the subject of extensive research, particularly in the field of space exploration. However, under certain conditions, the electrical power from a fuel cell is dependent on the gaseous fuel it receives, so that the use of such devices as analytical gas sensors is possible. This subject has been extensively researched in the UK, to the point where analytical fuel cell detectors for ethanol and formaldehyde are now on the market, and an adaptation of such device was proposed as a suitable detector for air infiltration measurements. The fuel cell detector, shown in simplified form in Figure 10, is constructed from porous PVC discs (30 mm  $\phi$  x 1 mm) which have been gold plated on each surface to form the electrodes of the cell. After electroplating, the discs are immersed in phosphoric acid electrolyte. The cell is then mounted in a sealed plastic moulding with the necessary electrical contacts. The plastic moulding provides a small deadspace volume above each electrode, together with the inlet and outlet ports above the anode plate.

The general principle of the anlaytic fuel cell is quite simple although the exact chemical reactions which take place are not clearly understood. At one electrode, the anode, one chemical compound is reduced and at the other, another chemical compound is oxidised. Therefore, the essential requirement for the fuel cell to operate as an analytical sensor is that the chemical to be detected must be either oxidisable or reducible, at the particular electrode surface, the former applying to most situations. The electrical response of the cell to the presence of an oxidisable gas introduced through the sample port is proportional to the quantity of gas which is absorbed onto the face of the electrode, and hence which is present in the gas sample. Since the absolute quantity of the oxidisable gas is small, the oxygen requirement to complete the reaction at the cathode is correspondingly small, so that diffusion from the air in the deadspace is sufficient. The fuel cell may be used to measure ethanol vapour in the parts per million concentration range, when the following reactions are thought to occur.

At the anode (working electrode)

 $CH_{3}CH_{2}OH$  -  $CH_{3}CHOH + H^{+} + e$  $CH_{3}CHOH$  -  $CH_{3}CHO + H^{+} + e$ 

At the cathode (reference electrode)

 $H_20 + \frac{1}{2}0_2 + 2e - 20H^-$ 

Electrons generated by the oxidation process cause the working electrode to become polarised with respect to the reference electrode. In all applications, the working electrode is therefore depolarised by connecting a small external resistance across the cell electrodes. The small potential difference, in the order of millivolts, generated across this resistor by the electron flow is an indication of the quantity of gas at the working electrode. A typical response curve is shown in Figure 11. The external resistance gives rise to an exponential discharge curve, and the combination of this with the charge curve due to the ethanol oxidisation results in the overall response curve characterised by the rapid increase in output to a peak followed by an exponential decay. The level of the peak voltage is directly related to the concentration of fuel in the cell.

#### 4.2.3.3 Advantages of the Fuel Cell Transducer

The main advantages of the fuel cell transducer in its basic form are:

- (a) small size, 80 x 60 x 30 mm.
- (b) low weight, 100 gm.
- (c) no power requirement
- (d) low threshold value of detection, a few parts per million
- (e) low cost, about £100.

As a result of these advantages it was decided to purchase two fuel cell units for laboratory trials using ethanol as the tracer gas.

### 4.2.3.4 Detailed Investigation of Fuel Cell

The following conclusions were reached as a result of the detailed investigation of the fuel cell:

- (a) its output is strongly temperature dependent. When sampling air at 21°C containing ethanol at 190 ppm, the fuel cell produced peak outputs of 5.0mV at 21° (Figure 11) and 6.6mV at 61°C (Figure 12). To maintain the fuel cell at a temperature of approximately 60°C the manufacturers produce an electrically heated pad which is placed around the fuel cell. A proportional temperature controller was constructed to control the heating power of the pad and thereby hold the temperature of the fuel cell within 0.3°C of the set temperature.
- (b) the time required for it to reach its peak output is dependent on temperature, and possibly on tracer concentration.
- (c) the time required for the output to decay to a low level that will not interfere with the next measurement is dependent on temperature, on the external resistance of the measuring circuit and possibly on tracer concentration.

- (d) the cell produces a spurious output if ethanol is present in the ambient air.
- (e) each fuel cell must be individually calibrated.

# 5. FUEL CELL AND INFRA RED GAS ANALYSER MEASUREMENT SYSTEMS

### 5.1 Preliminary Design for System using Fuel Cell Analysers

# 5.1.1 General

Figure 13 shows a preliminary desgin for a multi-point tracer gas concentration measurement system using fuel cell gas analysers. 30 measurement points for concentration and temperature were assumed.

Each fuel cell analyser unit as shown in Figure 13 consists of the fuel cell itself, an electrically heated jacket with thermostatic control, a solenoid actuated diaphragm sampling pump and a thermocouple for measurement of ambient temperature.

The microcomputer controls the scanners, multimeter, printer and disc drive so as to:

- (a) select individual fuel cells, thermocouples and other instruments for connection to the multimeter by the scanners and measurement of their output by the multimeter,
- (b) receive the measurements from the multimeter,
- (c) translate measured outputs into physical quantities using calibration data,
- (d) record tracer gas concentrations, temperatures and other data on disc,
- (e) print out selected data and operating information,
- (f) command the fuel cell analysers to take samples and to reset after completing each measurement.

# 5.1.2 Technical Problems

A number of technical problems were expected with this system. These are discussed below.

A considerable amount of work was required to establish whether the fuel cell analyser could achieve sufficient speed and accuracy, and to repackage it in a suitable form (incorporating an ambient temperature measurement, an electrically heated enclosure with thermostatic control and remote control of the analyser itself).

The output of the fuel cell analyser rises to a peak and then falls after a sample has been taken, the peak output indicating the tracer gas concentration. The microcomputers which would be suitable for this application on the basis of price, input/output capability and ease of programming tend to be rather slow and thus the computer might be unable to scan serveral fuel cells simultaneously and calculate the peak outputs of each in addition to tis other tasks. The alternative of operating and monitoring one fuel cell at a time could be too slow, as the fuel cell takes about 30 seconds to reach its peak output. Allowing some time for other tasks and some variation of the speed of the fuel cell, 30 cells could each be served by the computer at approximately 30 minute intervals. A higher sampling frequency than this was expected to be required.

The long signal lines from the fuel cell analysers back to the computer and its peripherals would be liable to interference which could lead to inaccuracies or even inability to perform measurements.

The fuel cell analysers are designed to measure the concentration of ethanol vapour in the air. High vapour concentrations near the ethanol source would be probable and would create a considerable fire hazard.

The calibration of thirty or more fuel cells would be very costly and time consuming.

#### 5.1.3 Estimated cost

The cost of the system shown in figure 13 was estimated to be about  $\pounds 23000$ , not including equipment required for fuel cell calibration, erection on site, etc.

# 5.2 Preliminary Design for System using Infra-red Gas Analysers

#### 5.2.1 General

Figure 14 shows a preliminary design for a multi-point tracer gas concentration measurement system using infra-red gas analysers.

The gas analysers measure the concentrations of nitrous oxide tracer gas in the samples. Each gas analyser is connected to ten sampling tubes by valves, one of which would be open at a time. Air continues to be drawn through the sampling tubes not connected to the analysers, so that the analysers always recieve fresh samples. The gas analysers have automatic calibration and two ranges with automatic range selection.

The microcomputer controls the scanners, multimeter, printer and disc drive so as to:

- (a) command the sampling valves to connect individual sampling tubes to the gas analysers,
- (b) select individual gas analysers, thermocouples and other instruments for connection to the multimeter by the scanners and measurement of their output by the multimeter,
- (c) receive the measurements from the multimeter,
- (d) translate measured outputs into physical quantities using calibration data,
- (e) record tracer gas concentrations, temperatures and other data on disc,
- (f) print out selected data and operating information,
- (g) command the gas analysers to carry out automatic selfcalibration and recieve status information from them.

### 5.2.2 Technical Problems

The technical problems of the infra-red gas analyser system were expected to be much less severe than those of the fuel cell analyser system. All the main components are proven commercial products, and the main problems were expected to be those of interference with signals by voltage transients from relays, solenoid valves, etc and those of suitable buffering and translation on the signal lines between the various instruments.

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The infra-red gas analysers take about 20 seconds to reach a steady reading after a change in tracer concentration in the air being sampled. Unlike the fuel cell analysers, they produce a steady output indicating the tracer gas concentration, thus it is only necessary to measure their output after it has stabilised. Three anlaysers could each be served on a 30 second cycle, allowing 20 seconds for each analyser to stabilise and 10 seconds for the measurement. Thus 30 sample points could be served on a 300 second cycle.

# 5.2.3 Estimated Cost

The cost of the system shown in figure 14 was estimated to be about \$31000, not including calibration gases, equipment for erection on site, etc.

# 5.3 Choice of Measurement System

The cost advantage of the fuel cell system was insufficient to outweigh the performance and convenience advantages of the infra-red system. The infra-red system was therefore selected.

# 6. PRELIMINARY VENTILATION RATE MEASUREMENTS

# 6.1 Measurements in a Medium-sized Enclosure

# 6.1.1 Enclosure and Instrumentation

Figures 15 to 17 show the general arrangement of the test enclosure and the positions of the measurement points. The building has brick cavity walls and a roof of asbestos sheets covered in roofing felt. The line of the roof is broken by monitors with glazed sides and some opening lights. The test space is separated from the main laboratory by a timber-framed partition. Offices within the test space are separated from it by brick walls and a timber floor above. The test space is heated by a radiator and two fan convectors at low level and by heating pipes which run around the monitors at high level. Fans have been installed to permit the mixing of the air within the space to be improved.

The arrangement of the instrumentation used to carry out the measurements was generally as shown in Figure 14, but only 10 measurement points were used. The measurements of wind velocity and direction were omitted.

# 6.1.2 Measurement method

The measurement method used was to inject tracer gas into the air in the space and then observe the decay of the gas concentration with time. If perfect mixing were obtained, the ventilation rate could be obtained from the following equation:

$$\ln C_{t2} = C_{t1} - Q_{v} (t2 - t1)$$

where

C<sub>tl</sub> = tracer gas concentration at time tl

 $C_{+2} = tracer gas concentration at time t2$ 

This is the equation of a straight line with gradient -Q on a graph of lnC against t.  $\overline{v}$ 

It has already been described (Section 2.4) how if perfect mixing were not obtained, the tracer gas concentrations would be different at different points in the space. The lines on the graph of lnC against t may have different gradients, and would in general not have the gradient - Q.

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#### 6.1.3 Results of Measurements

Figures 18 and 19 show the tracer gas concentration decays obtained in two tests.

In test 4 (Figure 18) good mixing was obtained by natural air movement in the space, and the points showing the tracer gas concentrations lie for all practical purposes on the same line. The ventilation rate obtained from this line is 0.40 air changes per hour.

In test 2 (Figure 19) good mixing was obtained initially, but after about 50 minutes the air movement pattern changed and mixing became noticeably imperfect. The slope of the first 50 minutes of the curve indicates a ventilation rate of 0.41 air changes per hour. The slope of the upper group of points from 80 minutes onwards indicates an apparent local ventilation rate of 0.28 air changes per hour, while that of the lower group indicates an apparent local ventilation rate of 0.49 air changes per hour.

Positions C and H, which have the lower tracer gas concentrations, are located in the monitors at the top of the test space. The remaining positions are located in the main volume of the enclosure. Tracer gas concentrations from positions I & J are not shown on figures 18 and 19 due to limitations of the computer program for graph plotting, but they do not affect the pattern of the results.

# 6.1.4 Analysis of Results

The results shown in Figure 19 were analysed manually by a simplified version of the method described in Section 2.5. The total ventilation rate of the space was calculated to be 0.3 air changes per hour. Since the ventilation rate during the first part of the test was about 0.4 air changes per hour, this result seems reasonable. It is not yet possible to set margins of error for the calculation of ventilation rates when mixing is imperfect.

# 6.2 Measurements in a Large Enclosure

# 6.2.1 Enclosure and Instrumentation

Figures 20 and 21 show the general arrangement of the test enclosure and the positions of the measurement points. The constructional features of the test enclosure are described in Table 1 (building A).

The arrangement of the instrumentation used to carry out the measurements was generally as shown in Figure 14, but only 9 measurement points were used. The measurements of wind velocity and direction were omitted.

# 6.2.2 Measurement Method

This was the concentration decay method as described in 6.1.2.

# 6.2.3 Results of Measurements

Some preliminary measurements were carried out in this building before work on improving its airtightness was begun (see section 7).

Concentration decay curves from a typical test are shown in Figure 22. Fairly good mixing was obtained about 4 hours after the start of the test. The slope of the concentration decay curves after this time indicates a ventilation rate of about 0.25 air changes per hour. This test was conducted with all doors, windows and ventilators closed and the building unoccupied. The temperature difference between inside and outside was between 0 and  $3^{\circ}$ C. The wind velocity was estimated to be less that 1 m/s.

As the conditions under which the test was performed were rather unusual, the infiltration rate in this building would normally be considerably higher than that measured in this instance. If the speed of mixing does not increase in proportion to the infiltration rate, then under normal conditions good mixing may not be attained before the tracer gas concentrations have become too low to be measured accurately.

### 7. VALIDATION OF MEASUREMENT METHOD

#### 7.1 Need for Validation

It has been established that imperfect mixing is likely in large enclosures such as factories and warehouses, and the fundamentals of a tracer gas method for measuring ventilation rates in such spaces have been outlined.

Before using the tracer gas method in practice, it is necessary to confirm that the ventilation rate measured by it is similar to the true ventilation rate of the space. This is because the calculation method for interpreting the results involves assuming that the space is divided into well-mixed zones of known shape and size. This assumption will be generally untrue, but it is necessary to discover how large an error is introduced by it.

# 7.2 Method of Validation

To validate the ventilation rate measurement method, measurements will be carried out in a large enclosure with a controlled ventilation rate and, if possible, various patterns of imperfect internal mixing.

To obtain a controlled ventilation rate, a moderately airtight enclosure is required. When air is supplied to or extracted from the enclosure by a fan (see figure 23), the air leakage through the envelope will create a pressure difference between inside and outside. A suitable combination of envelope airtightness and forced ventilation rate will create a pressure difference that is larger than the pressures due to wind or temperature differences. Thus the pressure difference and therefore the air flow will have the same direction over the entire envelope, and the flow rate through the fan will be the true ventilation rate of the enclosure. The flow rate through the fan can be measured by mechanical methods and compared with the ventilation rate measured using tracer gas. A number of industrial buildings were examined with a view to finding one with a suitable standard of airtightness for the validation work.

Two buildings (referred to here as building A and building B) were pressure tested.

Drawings of building A are shown in figures 20 and 21 and of building B in figures 24 and 25. The essentials of the airtightness test method are shown in figure 26. The main constructional features of the buildings and the results of the airtightness tests are summarised in Tables 1 and 2 respectively.

The striking features of the results in Table 2 are the generally high leakiness of the buildings and in particular the high leakiness of the roller shutter door of building B.

Neither of the buildings were sufficiently airtight for the validation work. Although building A was leakier, it appeared that it would be easier to improve its standard of airtightness. It was therefore selected for the tests and work was begun on sealing the air leakage paths.

# TABLE 1

# Constructional Features of 2 Industrial Buildings

Feature	Building A	Building B
Floor	Concrete slab on ground	Concrete slab on ground
Roof	Double skin asbestos sheets with glass fibre insulation between skins	Corrugated steel sheets, rigid insulation, roofing felt
Party walls	Brickwork	Brickwork
External walls	Corrugated steel sheets with plasterboard lining and glass fibre insulation between	Brickwork with metal-framed windows above
Goods doors	2 steel roller shutters	l steel roller shutter

# TABLE 2

# Summary of Results of Airtightness Tests of 2 Industrial Buildings

	Building A	Building B
Fan airflow rate, m <sup>3</sup> /s	4.9	4.9
Forced air change rate, per hour	2.6	3.1
Pressure differences between inside and outside (Pa) with:		
All doors, windows, ventilators and flues sealed	≃ 0	12
All windows, ventilators, flues and personnel doors sealed. Goods door(s) not sealed	≃ 0	2.5
	-	

Doors, windows, ventilators and flues were sealed by covering them with polythene sheet taped to the surrounding building structure.

Wind interfered with the testing of building A, making it difficult to obtain accurate results.

360.00 330.00 300.00 270.00 240.00 210.00 \* 10° 120.00 150.00 180.00 TIME (SECS.) ♦ = ZONE 8
♦ = REAN
X = PERFECT RIXING 30.00 60.00 ~ (V SIN 4 G = 20NE C = 20NE + 20NE + 20NE + 20NE X = 20NE 30.00 00.00 00.8 CONCENTRATION (PPM.) 00-2 . г.оо г.И. 00-1

FIGURE 1

TRACER GAS CONCENTRATION DECAYS SIMULATED

360.00 330.00 300.002 270.00 240.00 210.00 \*10° 120.00 150.00 180.00 TIME (SECS.) 30.00 60×00 

 G
 =
 ZONE
 2

 O
 =
 ZONE
 2

 A
 =
 ZONE
 4

 +
 =
 ZONE
 5

 X
 =
 ZONE
 5

 30.00 00.00 00.8 CONCENTRATION (PPM.) 00-2 2.00 LN. 00-1

FIGURE 2

GAS CONCENTRATION DECAYS TRACER SIMULATED

# SIMULATED TRACER GAS CONCENTRATION DECAYS



All zones 1000 m<sup>3</sup> Air flows in m<sup>3</sup>/s.



All zones 1000m<sup>3</sup> Air flows in m<sup>3</sup>/s.



All zones 1000m<sup>3</sup> Air flows in m<sup>3</sup>/s.







4.35





SCHEMATIC OF FUEL CELL SENSOR



40

4-0





PRELIMINARY DESIGN OF TRACER GAS CONCENTRATION MEASUREMENT SYSTEM USING FUEL CELL GAS ANALYSERS



PRELIMINARY DESIGN OF TRACER GAS CONCENTRATION MEASUREMENT SYSTEM USING INFRA-RED GAS ANALYSERS







GAS SAMPLING POINTS

LINE OF SECTION

BOOKSHELVES WITHIN TEST ENCLOSURES

THERMOCOUPLES

0

+

 $\boxtimes$ 

**A** 

FIRST FLOOR PLAN OF MEDIUM SIZED ENCLOSURE





# MEASURED TRACER GAS CONCENTRATION DECAYS









PLAN OF BUILDING A





4.48





TEST METHOD FOR VALIDATION OF TRACER GAS VENTILATION RATE MEASUREMENT





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TEST METHOD FOR BUILDING AIRTIGHTNESS

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