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PAPER 3

DEVELOPMENTS IN A MULTI-TRACER GAS SYSTEM AND MEASUREMENTS USING PORTABLE SF_6 EQUIPMENT.

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ABSTRACT

In this paper we describe the development of a multi-tracer gas system for measuring interzonal air movement in buildings. The system consists of simple and stand-alone gas injectors and sampling units. The injectors are capable of releasing up to four perfluorocarbon tracer gases in different parts of a building. Following tracer gas injection and mixing, small samples of air are collected using automatic sampling units. Each unit consists of a 16-position valve and a group of removable stainless steel tubes packed with solid absorbent. Samples may be taken simultaneously at up to four points in space and up to 16 points in time. These samples are then stored for subsequent analysis in the laboratory using an automatic thermal desorber and gas chromatograph.

In the second part of the paper, the portable sulphur hexafluoride (SF_6) system is described. The system incorporates an electron capture detector gas chromatograph and operates automatically using a BBC microcomputer. Using this system the air change rates were measured in a number of recently constructed houses in the Milton Keynes area, UK. The test data of various measurements are presented together with an analysis of the results.

1. INTRODUCTION

One aspect of energy conservation attracting attention at present is the reduction of heat losses in buildings derived from poor thermal insulation and high air infiltration rates. As a result a large number of superinsulated houses are being built in Scandinavia, North America and recently in the UK[1]. These bouses are constructed in such a way that air leakage through cracks and openings in their envelopes no longer serve as a source of ventilation and so mechanical ventilation systems are required. Inadequate air change rates give rise to an increase in indoor air contaminants (eg., formaldehyde, nitrogen dioxide and moisture) which have an important influence on the health and comfort of the building's occupants. Research is therefore required to evaluate the extent of air ventilation and dispersion of interior contaminants so that the optimum compromise between energy consumption and sufficient air change to maintain a healthy environment is achieved.

The air tightness of buildings can be examined by pressurisation using blower doors. Unfortunately, this technique is unable to provide information on air infiltration in a building under natural climatic conditions. As an alternative, tracer gas techniques may be used for measuring air change rates in buildings. Reviews of various tracer gases and measuring techniques have been made by Harrje et al[2], Sherman et al[3], and Lagus and Persily[4]. Until recently, measurement of air movement has usually involved the assumption that the building is a single uniformly mixed zone. However, multizonal measurements are essential if movement of indoor air contaminants and energy transfer among various parts of the building is to be accurately represented. The measurement of interzonal air flows in buildings, such as hospitals, is important as the transport of odours and bacteria between various ward units must be kept to minimum[5].

The use of a multi-tracer gas, instead of a conventional single gas method, increases the speed and accuracy of interzonal air flow measurements[6]. It also clarifies specific flow directions. Gases which have been used include carbon dioxide, nitrous oxide, hydrogen, methane, ethane, helium, perfluorocarbons (PFTs) and sulphur hexafluoride. We have used perfluorocarbons and sulphur hexafluoride in our work as they have desirable tracer gas characterisitcs in terms of detectability, safety, and cost and they have been used successfully in air infiltration studies[6,7,8,9]. Both SF_6 and PFTs exist only at very low background concentrations in the ambient and are easily detected (parts per billion range for SF_6 and parts per trillion range for PFTs) using an electron capture detector.

This paper is divided into two main sections. The first describes the development of the multi-tracer system for measurement of interzonal air flow in buildings. The second section describes a portable automated SF_6 system which has been used for measuring air change rates in a number of recently constructed tightly sealed houses in Milton Keynes, UK. The design, construction and calibration of the SF_6 system together with experimental results is also presented.

2. DEVELOPMENT OF A MULTI-TRACER GAS SYSTEM

Experimental work on interzonal air movement was previously carried out by Prior et. al.[10] at PCL using an unrefined system consisting of automatic injection and sampling systems. During the present work this system has been improved with the development of the following:

2.1 Tracer Gas Injection

The rate of decay technique is used in our work as it requires relatively simple apparatus.
A number of injection units are being built. These simply consist of a 10 ml aluminium cylinder wrapped with a band heater and fitted with a sealing cap, Figure 1. Prior to each experiment, cylinders are injected with a known amount of perfluorocarbons and sealed in the laboratory. A programmable timer is used to energize the band heater during the test allowing tracer gases to be released simultaneously into a building. The following perfluorocarbons have been used in our work; perfluoro-n-hexane, perfluoro-methyl-cyclohexane, perfluoro-dimethyl-cyclohexane, and perfluoro-decalin.

2.2 The sampling System

The microcomputer-sampling system developed by Prior et al[11] may be improved with the following benefits: 1) greater speed of deployment within buildings, 2) a more compact and flexible system so it can be used during periods of a building occupancy, 3) reduced capital cost of the system.
The design of a compact and stand-alone sampling system is shown in Figure 2. The sampler consists of a 16-position, 34-port valve (type ST flowpath), made by Valco Instruments. The valve has an inlet port, an outlet port and a pair of ports at each of the 16 sampling positions. A six-position version of this valve and a sampling tube is shown in Figure 3. A small removable stainless steel tube, Figure 4, packed with a divinyl-benzene/styrene co-polymer adsorbent is connected to each pair of valve ports. Air at a constant flow rate may be drawn in each sampling point using a small pump and the multi-position valve is positioned by a stepping motor. A two channel digital timer is used as a control system to operate the stepping motor and pump. The operation procedure of the system is as follows. At the beginning of each experiment the valve is rotated to position 1 and the pump is turned on. At the end of the desired sampling collection time, set by the timer, the pump is turned off and the valve is rotated to position 2. This procedure is repeated

until all samples have been taken. The system is flexible since the sample loops may be filled in any desired sequence and at any desired time. The samples may be then stored for subsequent analysis in the laboratory.
Work has been completed on building one sampling unit and we are currently building further units of a similar design.

2.3 Tracer Gas Separation and Analysis

A new gas chromatograph, model 8410, made by Perkin Elmer is currently being commissioned. The chromatograph, which is fitted with an electron capture detector (ECD) and an ATD-50 thermal desorber, will be used for separation and analysis of the samples.

2.4 Measurements and Simulation Models

The new multi-tracer gas system will be used for measuring air movement in a number of recently constructed houses in the Milton Keynes area. Measurement will be carried out in other passive solar heated houses at Newham, UK. Some measurements may be carried out in Central Europe, providing suitable projects are located.
In the second phase of our programme, a comparison will be drawn between measurements of interzonal air flow and rates predicted using rules of thumb such as those developed by Balcomb et. al.[12] and using simulation models such as BREEZE and ESP[13]. In order to make comparisons with these models, work will begin on the implementation of the latest versions of the codes, at PCL, in the near future.

3. THE PORTABLE SF_6 SYSTEM

3.1 DESCRIPTION OF THE SF6 SYSTEM

The SF_6 system used in this study consisted of the following:

3.1.1 The SF_6 Release System

The SF_6 release system consisted of a small SF_6 cylinder, a regulator and a solenoid valve. The solenoid valve is normally closed but is opened automatically using a BBC microcomputer. The volume of SF_6 gas released depends on the size of the building and is controlled by adjusting the length of time that the solenoid valve is open. The injection rate was determined by plotting the volume of gas released against time required for a constant pressure at the SF_6 cylinder outlet.

3.1.2 The SF_6 Measuring System

The microcomputer-measuring system is shown in Figure 5. The system was made up from the following major components:

(a) Sampling and Injection Unit

(b) Column

(c) Chromatographic Oven

(d) Electron Capture Detector

(e) Microcomputer and Interface

The operation of the system is described, with reference to Figure 6. Argon, used as the carrier gas, normally flows at a constant rate through the column via the sampling valve. The carrier gas then passes through the detection cell before being vented to the atmosphere. The sampling unit consists of a two-position, 6-port valve, connected to a 0.5 cm^3 sampling loop. The valve can be easily rotated to position 1 or 2 using a small motor.
The column was made by packing a 1.5 m x 4.3 mm i.d. nylon tube with 60-80 mesh aluminium oxide. The tube was coiled three times and placed horizontally inside an electrically heated oven. The oven was maintained at a constant temperature using a temperature controller. The electron capture detector, which uses Ni-63 radioactive cell, was made by Pye Unicom Ltd. This was also placed inside the oven as shown in Figure 5. A pump was used to draw air from the test space to create a flow through the sample loop. By rotating the sample valve to position 2, air in the sample loop was injected into the argon flow which carried it into the column and finally to the detector for analysis. The amplified reversed response from the detector cell is then displayed as peaks on the computer monitor as shown in Figure 6. The first peak represents the O_2 concentration in the sample and the second peak represents the SF_6 concentration.
The system incorporates a BBC micro-computer with two $5\frac{1}{4}$ inch dual sided floppy disc drives, a parallel printer and interfaces for both analogue and digital data. The interfacing of the gas chromatograph and the sampling and injection units was accomplished by specially designed interface cards. The system is very flexible and can be used for unattended operation.

3.2 System Calibration

Calibration of the SF_6 system was carried out using the test rig shown in Figure 7. The rig consisted of 0.215 m^3 capacity metal drum in which a small fan was used for mixing air and tracer gas. Air from a cylinder was line fed to an opening in the drum and its flow rate could be regulated between 10-150 and 100-1250 liters/hours using Brooks Ltd. Flowmeters. Provision was made

for the injection of SF_6 tracer gas into the drum and also for allowing the homogeneous SF_6/air mixture to leak out through a tube. Samples of SF_6/air mixture were drawn into tubes located at different levels in the drum. These samples were then passed through the ECD gas chromatograph for analysis.
Experiments were conducted for infiltration rates in the range 0.1 to 2 air change/hour. The variation of measured air change rates using the SF_6 system versus calculated values using the flowmeters is presented in Figure 8. The coefficient of correlation was found to be 0.9947, the slope was 0.941 with an average error of 1.1%. The series of experiments showed that the portable SF_6 system gives reliable results.

3.3 TRACER GAS MIXING

The lack of good mixing of tracer gas with air could result in inaccurate measurement of the air change rate. Even so, a number of workers assume the concentration of tracer gas in a space is uniform and therefore measure the concentration at one point. Mixing problems may arise from buoyancy effects or from poor air circulation within the space due to internal partitions such as walls and furniture[14].
To study buoyancy effects we carried out a number of tests in a closed container. A small amount of SF_6 was injected at the top of the container before it was sealed and left for about 45 minutes. The concentration of SF_6 was then measured at different heights. The concentration of SF_6 was found to be greater in the lower quarter of the container. Experiments were repeated with SF_6 injected at the lower part of the container with similar results being obtained. As a circulation fan was not used in our experiments it was suggested that the non-uniform concentration might be due to a slow mixing. To check this possibility the SF_6 was left in the container for a longer period and after about 2 hours the concentration of SF_6 was found to be uniform at various heights.
This experiment indicated that in tightly sealed houses an adequate period must be allowed for natural mixing and that buoyancy is not a problem with SF_6.

4. MEASUREMENT AND RESULTS

The tracer decay method has been used for measurement of air change rates in buildings. The decay method involves the release of a known volume of tracer gas into a building allowing sufficient time for the gas to mix with the air so that a uniform concentration is achieved. The dilution of the tracer gas is then monitored and is related to the air change rate according to:

$$C = C_o \, e^{-(At)} \qquad (1)$$

Where C is the measured tracer gas concentration at time t, C_o is the concentration at t=o and A is the air change rate.

Taking the natural logarithms of both sides of equation (1) we have:

$$\ln(C) = \ln(C_o) - A\,t \qquad (2)$$

A plot of the best fit of ln(C) versus time is normally used to determine the air change rate. The volume flow of air, Q, in and out of the building is given by:

$$Q = A\,V \qquad (3)$$

Where V is the interior volume of the building.

Air change rates were measured in a number of houses using the portable SF_6 system. The houses were built in Milton Keynes, UK, in 1985 and have been monitored since January 1986 by the Research in Building Group at the Polytechnic of Central London with funding from the Commission of the European Communities[1]. Tests were carried out on these houses as follows:

4.1 Superinsulated Houses:

The superinsulated houses are three bedroomed, semi-detached units, each with a floor area of 75 m^2 and an attached garage. The houses were built to a superinsulated standard three times more than the stringent than the current UK building regulations. Vapour barriers were also installed for both the ceiling and walls of each house. A mechanical ventilation system with heat recovery is used to supply a controlled amount of fresh air and also reduce energy losses. This system was manufactured by BAHCO of Sweden, and uses an aluminium cross flow heat exchanger. The space and water heating are accomplished using a gas heating system.
During the test the ventilation system was used to introduce SF_6 into each house in order to achieve good distribution and mixing of the tracer gas. The amount of SF_6 released depended on the size of the building and also on the sensitivity of the detector. About 1 cm^3 of SF_6 was released per m^3 of space volume. Following an adequate mixing period, samples were taken every three minutes from several locations in the house to determine the degree of mixing and also to acquire an average concentration. With all windows and exterior doors closed measurements were taken on a house under the following conditions:

a) Ventilation system switched off.
b) Ventilation system operating in low mode.
c) Ventilation system operating in normal mode.
d) Ventilation system operating in boost mode.

The temperature difference between the inside and outside of each house and average wind speed during the measurement period were also recorded. The results of tests made in one of these houses are given in Table 1.

TABLE 1. AIR CHANGE RATE MEASUREMENTS IN SUPERINSULATED HOUSES

Time & Date	Condition	Air Change Rate (h^{-1})	Temperature Difference (°C)	Wind Speed (m/s)
18.00, 16/4	a	0.10	15.5	1.3
10.00, 29/3	b	0.60	13.0	5.0
11.00, 28/3	c	0.90	13.5	6.7
13.30, 28/3	d	1.10	12.2	7.5

4.2 Control Houses

Control houses are almost identical to those that are super-insulated but differ in that they are not provided with a vapour barrier and their degree of insulation is only marginally above the current Building Regulation requirements. The control houses are heated with gas heating systems while ventilation is provided using slot ventilators in window frames.
Air change rates were measured in these houses using the above method. Since these houses are not provided with mechanical ventilation systems, SF_6 was released at various points and fans were used to ensure that proper mixing was achieved. With all windows and exterior doors closed measurements were taken on a house under the following conditions:

a) All vents closed
b) Downstairs vents open.
c) Downstairs and upstairs vents open.
d) Slot ventilators removed and holes sealed with tape.

The decay of SF_6 under condition c) is shown in Figure 9. The results of measurements for three control houses are summarized in Table 2.

TABLE 2 AIR CHANGE RATE MEASUREMENTS IN CONTROL HOUSES

House No	Time & Date	Condition	Air Change Rate (h^{-1})	Temperature Difference (°C)	Wind Speed (m/s)
1	11.00, 24/2	a	0.23	15.0	2.5
	13.00, 24/2	b	0.52	14.0	4.0
	15.00, 24/2	c	0.87	14.1	3.0
	16.30, 24/2	d	0.31	14.0	3.2
2	11.00, 6/3	a	0.26	14.5	2.2
	14.00, 6/3	b	0.59	12.5	2.4
3.	15.30, 6/3	a	0.20	16.0	4.5
	17.60, 6/3	c	0.94	17.5	4.3

The above results indicate the effectiveness of the slot ventilators in controlling the air change rates.

4.3 Courtyard Houses

The courtyard houses are a group of highly glazed passive solar houses, each is a four bedroomed, detached bungalow, with a floor area of 130 m^2, Each house has a gas-fired heating system which uses a condensing boiler with zone control from thermostatic radiator valves. A BAHCO ventilation system with heat recovery was fitted in each of these houses.

House Number 1

Measurements of air change rates were carried out in this house with the ventilation system operating under the following conditions.

a) Low mode
b) Normal mode
c) Boost mode
d) High mode

The results are presented in Table 3, and the decay of SF_6 under condition b)is shown in figure 10.

House Number 2

This house is temporarily provided with a different type of ventilation system with heat recovery in order to test its performance. The system, which is manufactured by Genvex of Sweden, supplies both ventilation and domestic hot water using a heat pump. The following operational modes were used:

a) Ventilation system switched off

b) Ventilation system switched off and fireplace sealed

c) Ventilation system operating on normal mode

d) Ventilation system operating on high mode

A summary of the air change analysis is given in Table 3.

TABLE 3 AIR CHANGE RATE MEASUREMENTS IN COURTYARD HOUSES

House No	Time & Date	Conditions	Air Change Rate (h^{-1})	Temperature Difference (^{o}C)	Wind Speed (m/s)
1	16.00, 19/5	a	0.51	6.0	3.8
	12.30, 19/5	b	0.68	1.7	2.5
	14.00, 19/5	c	0.81	3.7	2.7
	15.00, 19/5	d	0.84	4.8	4.0
2.	13.00, 18/5	a	0.23	6.7	4.0
	14.30, 18/5	b	0.16	6.3	4.2
	20.00, 18/5	c	0.42	9.0	4.0
	00.30, 18/5	d	0.54	9.5	3.5

5 CONCLUSIONS

(1) The use of the compact micro-computer SF_6 system has proved to be a reliable and a sensible approach for measuring air change rates in buildings.
(2) If SF_6 is allowed to mix naturally, then a period of about 2 hours is found to be essential if accurate measurements are to be made. Introducing SF_6 via the mechanical ventilation system of a building was found to be a good method for achieving quick distribution and complete mixing of the tracer gas.
(3) The measurement of the background air change rate for the superinsulated houses showed they are within the performance range standards of Scandinavian houses. Both tracer gas and blower door tests showed comparable results and confirmed the

airthightness of these houses. Ventilation rates under other operational modes were found to correlate well with figures calculated from duct air flow measurements.
(4) The use of slot ventilators and adequate heating in control houses was found to be a satisfactory means for reducing condensation. However, the efficacy of this approach critically depends on the way in which these ventilators are used by the building's occupants.
(5) Air change rates in the courtyard houses were found to be within the recommended ASHRAE standard and the mechanical ventilation systems were found effective in controlling the level of ventilation required.

ACKNOWLEDGEMENTS

The authors wish to thank C J Martin for designing the SF_6 system.

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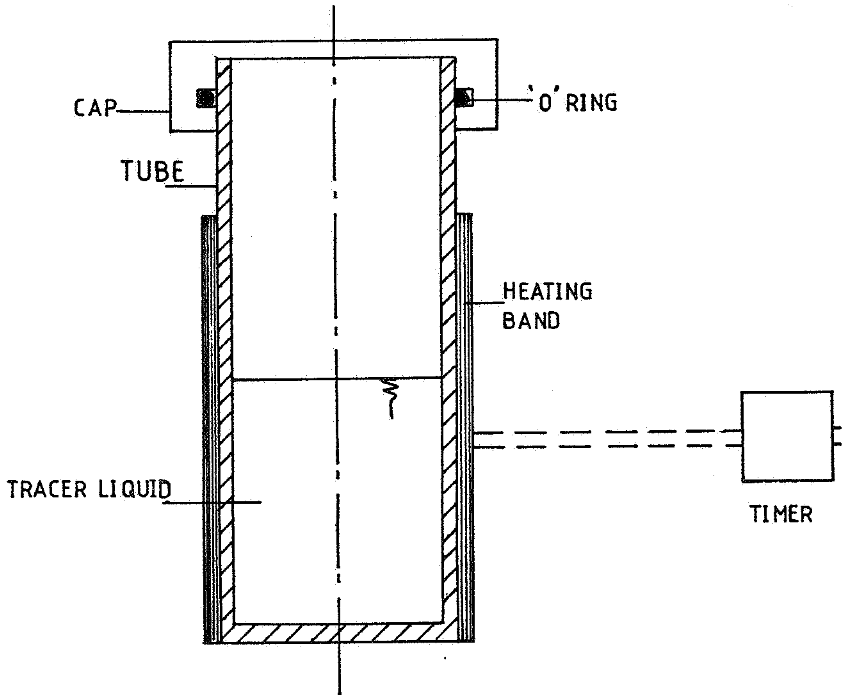

Figure 1
The tracer gas injection unit.

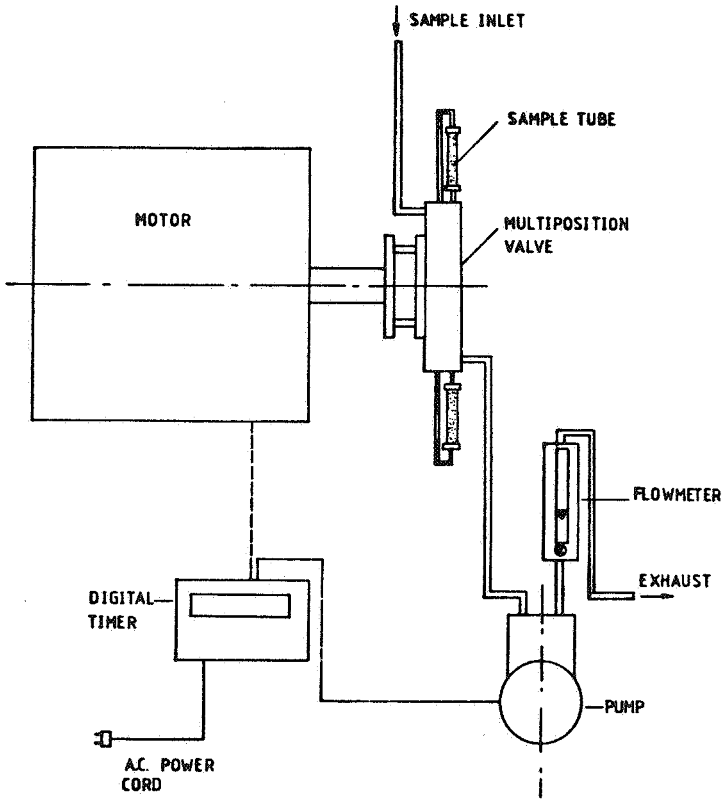

Figure 2
The multi-position valve sampling system

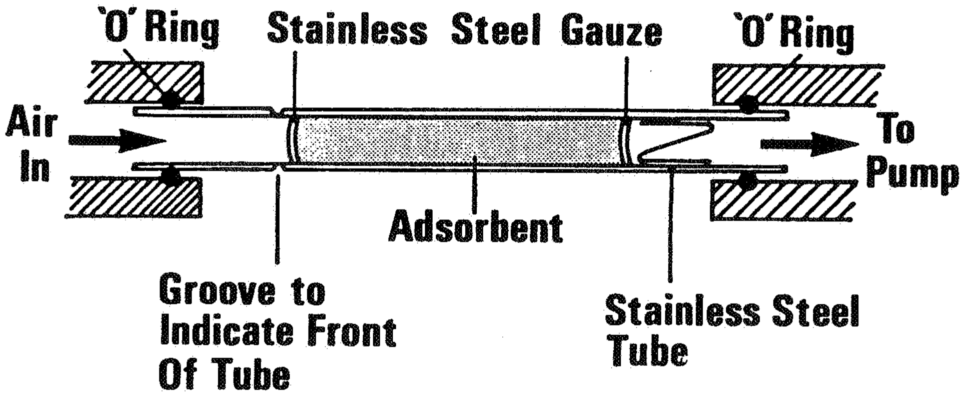

Figure 4
A single sampling tube.

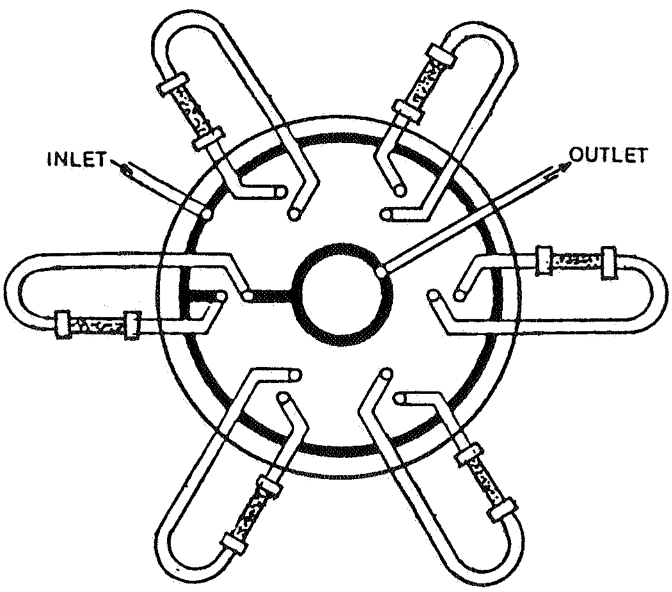

Figure 3
The six-position sampling valve

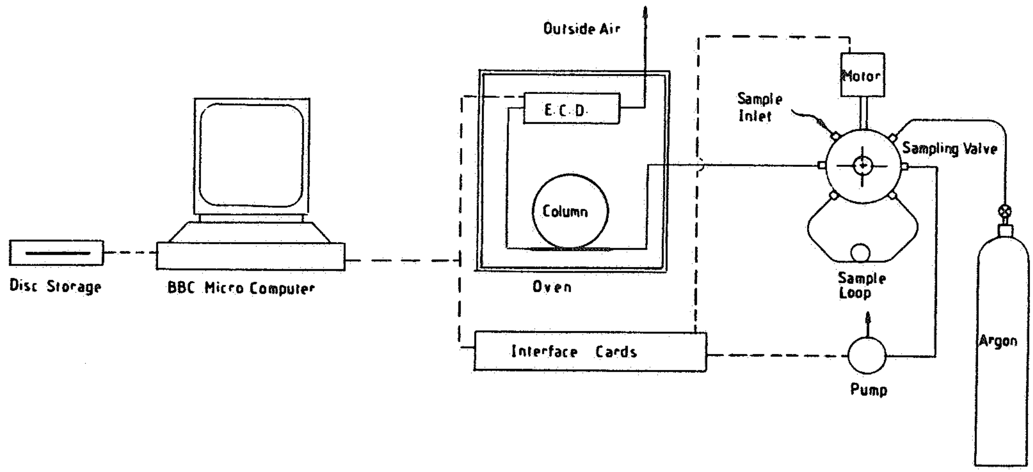

Figure 5.
The SF_6 System

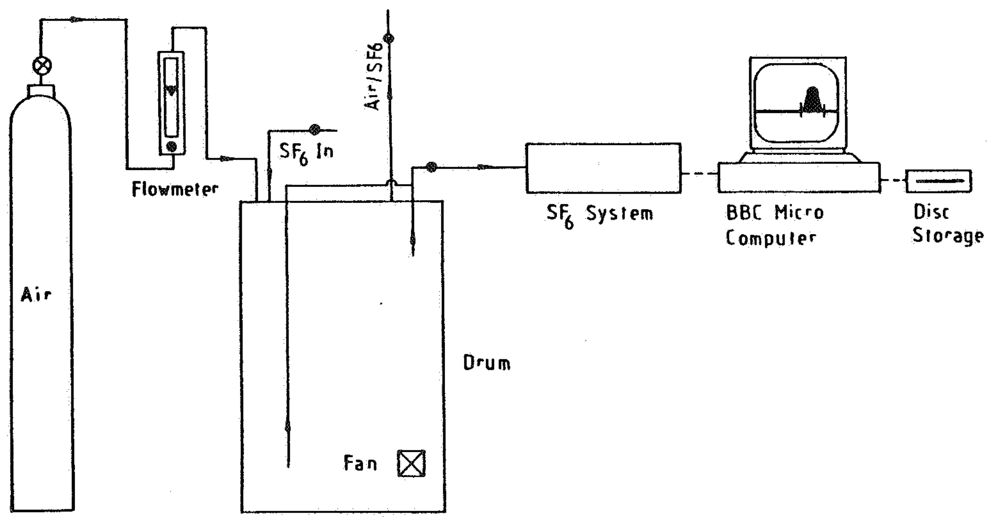

Figure 7
The SF_6 Calibration System

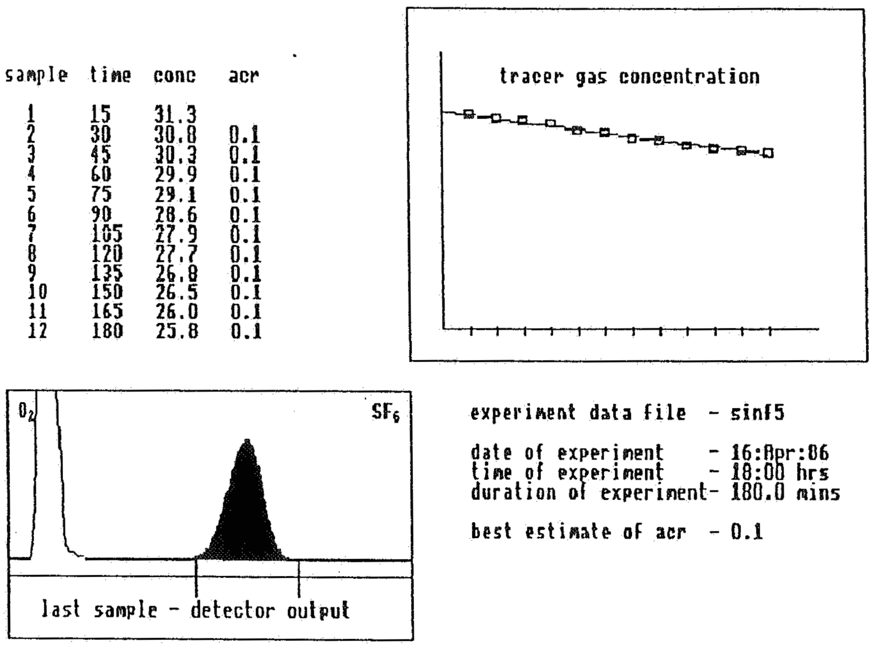

Figure 6

The SF_6 system output

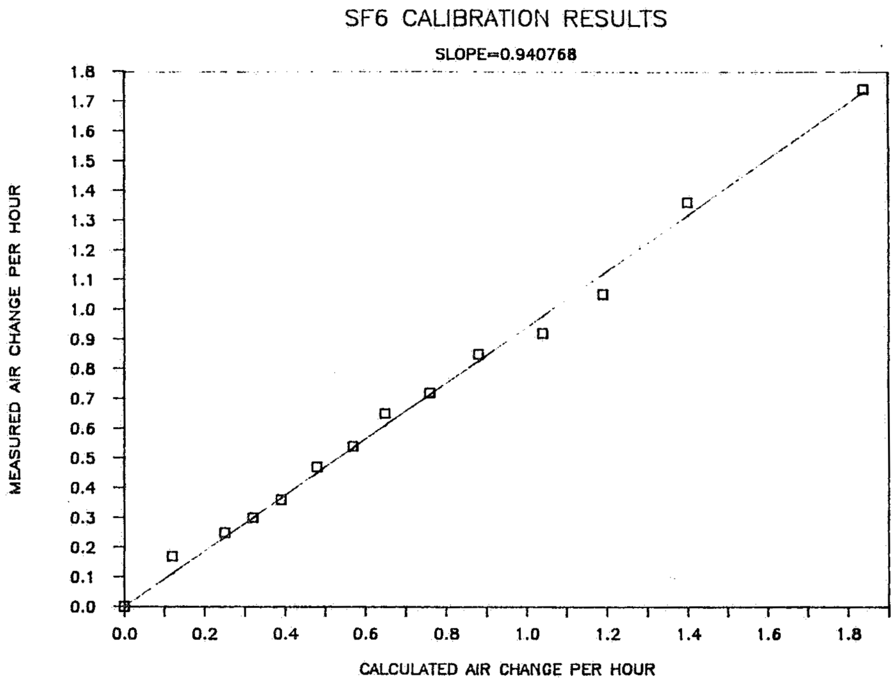

Figure 8

The variation of measured air change rates versus calculated air change rates.

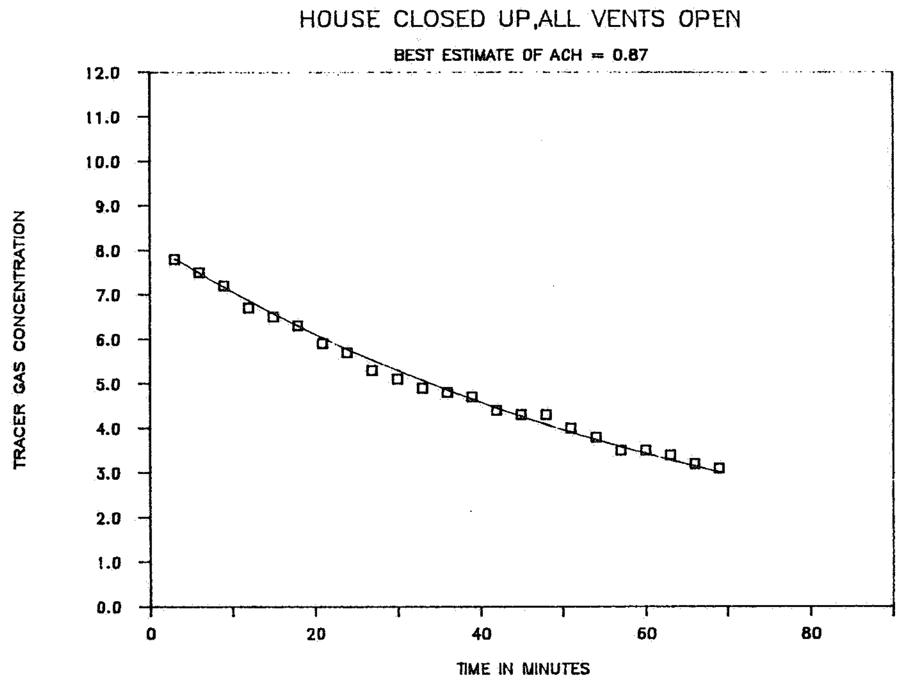

Figure 9
The decay of SF_6 tracer gas for a control house.

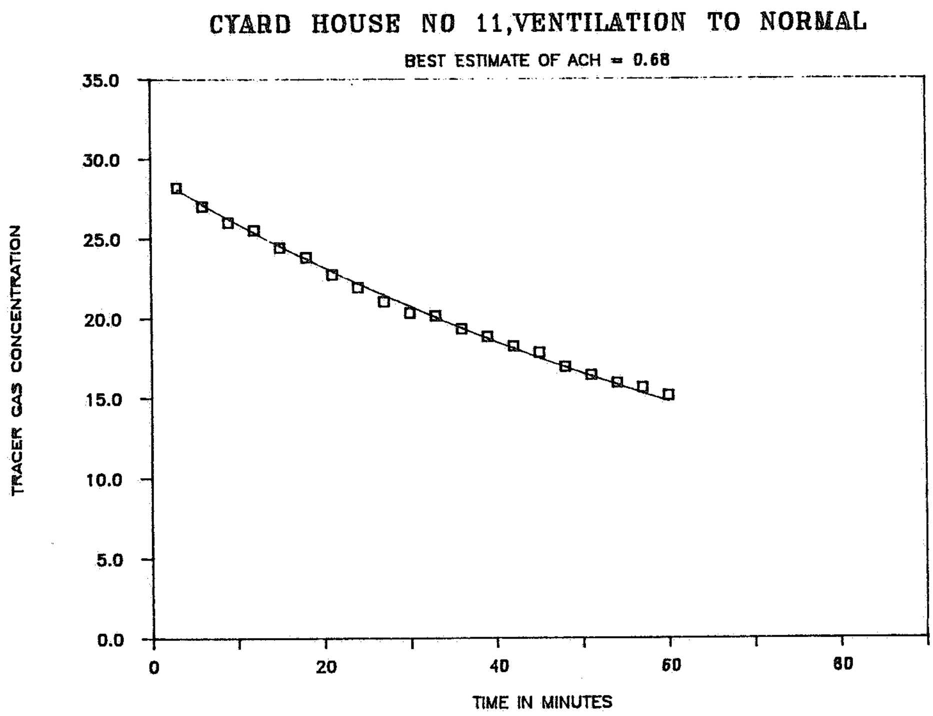

Figure 10
The decay of SF_6 tracer gas for the Courtyard house.