No. 2553

AN AUTOMATED AIR INFILTRATION MEASURING SYSTEM USING SF_6 TRACER GAS IN CONSTANT CONCENTRATION AND DECAY METHODS

R. KUMAR *Associate Member ASHRAE* **A. D. IRESON** **H. W. ORR**

ABSTRACT

One method of measuring rate of air infiltration in buildings involves the use of small amounts of a tracer gas. The concentration of the gas, which is measured at regular intervals, provides the basis for evaluating the infiltration rate. In the following paper, two bases for such evaluations are discussed - the decay method and the constant concentration method.

A system is described which automatically operates a portable electron capture detector/chromatograph and measures parts per billion concentrations of sulphur hexafluoride (SF_6) in air. It samples air on a 1-min. cycle. In the decay method, the slope of concentration vs time on a semilogarithmic plot can be used to compute the infiltration rate. In the second method, the system injects SF6 at the rate required to maintain the tracer gas at a fixed, predetermined level. The infiltration rate is proportional to the rate at which the tracer gas must be injected.

INTRODUCTION

The heat loss associated with air leakage through the enclosure of a typical detached house may be as much as 40% of the total heat loss. It is essential therefore to be able to estimate this component of the heat load with reasonable precision. But the variables, both physical and behavioral, that affect the phenomena of air infiltration and natural ventilation are not only numerous but also dependent on quantities that are difficult to measure and predict. Air infiltration can be caused by the passage of air through the cracks and other openings around windows and through walls, ceilings, roofs and floors of a building of any type; by the leakage in the air distribution system; by the need of the dwelling for combustion air for the heating system, etc. Each of these parameters can be influenced by the weather, the choice of building materials, the quality of the building construction, and the use of the building. By utilizing instrumentation that involves the direct measurement of air infiltration rates, it is possible to bypass the estimation and prediction difficulties. This paper deals with an automated approach to infiltration measurement using the tracer gas method, including principles of operation and design details, together with calibration procedure and preliminary field data on air infiltration.

R. Kumar, Division of Building Research, National Research Council of Canada, Saskatoon, Saskatchewan, Canada.

A.D. Ireson, Division of Building Research, National Research Council of Canada, Ottawa, Canada.

H.W. Orr, Division of Building Research, National Research Council of Canada, Saskatoon, Saskatchewan, Canada.

THIS PREPRINT FOR DISCUSSION PURPOSES ONLY. FOR INCLUSION IN ASHRAE TRANSACTIONS 1979, Vol. 85, Part 2. Not to be reprinted in whole or in part without written permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 345 East 47th Street, New York, NY 10017. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the author(s) and do not necessarily reflect the views of ASHRAE.

MEASUREMENT OF AIR INFILTRATION

(1) Decay Method

In the measurement of air infiltration by the decay method, a tracer gas is distributed in the air of a building and the decay in concentration is measured as a function of time. The theory of the method may be outlined briefly by considering the equation:

$$\frac{dc_i}{dt} = (c_o - c_i)\frac{V_1}{V_2} \qquad (1)$$

where c_o and c_i are, respectively, the concentrations of tracer gas outside and inside the building at time t. V_1 is the rate at which air enters the building. It is also the rate at which air leaves the building unless there is a build-up or loss of pressure. V_2 is the ventilated volume of the building, and V_1/V_2 is the air infiltration rate expressed in air changes per unit time.

If the outside concentration of tracer is small enough to be neglected, Eq 1 may be reduced to:

$$\frac{dc_i}{dt} = -c_i\left(\frac{V_1}{V_2}\right) \qquad (2)$$

Under conditions of perfect mixing, Eq.2 may be integrated to give:

$$\log_n\left(\frac{c_i}{c_{i_o}}\right) = -\left(\frac{V_1}{V_2}\right)t \qquad (3)$$

or

$$\frac{V_1}{V_2} = -\frac{1}{t}\log_n\left(c_i/c_{i_o}\right) \qquad (4)$$

where c_{i_o} is the initial indoor concentration of tracer gas. Since the equation involves the ratio of the tracer gas concentrations, any quantities proportional to the tracer gas concentration may be used to determine the air change rate. In practice, one usually selects an initial time, plots $\log_n(c_i/c_{i_o})$ against time, and determines the air infiltration rate from the slope of the line.

It should be noted here that the absolute value for concentration is not needed here, only relative values, since the ratio of concentrations is used in Eq 4. Hence the equipment does not need to be calibrated for concentration as long as the indication is linear. But the disadvantages of this method are: (i) it does not give continuous indication of infiltration rate; (ii) it is not a steady-state measurement, hence there could be problems involving the tracer due to its absorption and adsorption characteristics.

This method is limited to measuring infiltration rates for short periods since the initial amount of tracer is limited by maximum scale range of the detector/chromatograph. The period of measurement then is limited to the time required for the tracer to decrease in concentration from the initial maximum value to the minimum value limited by accuracy of measurement. If changes in air infiltration rate are slow, and there are no dead spaces, this is an acceptable method (1, 2).

(2) Constant Concentration Method

To overcome the problems inherent in the decay method, another method of measuring infiltration rate using a tracer gas was proposed by Orr (4). In this method the concentration of tracer gas is maintained at a fixed level.

For the measurement of air infiltration by the constant concentration method, a tracer gas is distributed in the air of a building to a certain concentration level. A sensing element is used to control the concentration of the tracer in the space. The amount of tracer gas required to maintain a constant concentration is then a direct function of the infiltration rate.

$$Q = cn$$

$$n = \frac{Q}{c} \quad (5)$$

$$n \propto Q \quad (6)$$

where Q - flow rate of tracer gas required to maintain a selective level, n = infiltration rate, flow rate per unit time, c = concentration in space (constant).

Advantages of the constant concentration method are that it is a steady-state mechanism and, hence, has no problems of adsorption and/or absorption. It gives an indication of infiltration rate in flow rate per unit time, which can be used for heat loss calculation without estimating the net internal space volume as for the decay method. The accuracy is dependent on measurement of the flow rate of the tracer gas and its concentration. The disadvantages of this method are that the flow control and its measuring apparatus are quite complicated. As a number of tracer gas injections is involved, thorough mixing of tracer gas and air can be more difficult to achieve than in the decay method with a single injection. Also, the absolute value of the concentration of tracer gas in space must be known.

In the present unit, constant concentration is achieved by controlling the number of injections of tracer gas of fixed quantity from the discharge unit. The air is sampled and the concentration is measured on a 2-1/2-min. cycle. The programmable calculator in the system can call up to 90 injections of tracer gas for the 2-1/2-min. period.

CHOICE OF A TRACER GAS

A wide variety of materials are being used as tracer gases. Of these, sulphur hexafluoride (SF_6) is particularly suitable for air infiltration studies involving continuous measurement and large buildings. The use of SF_6 was first reported as a tracer gas in 1965 (3). It has all of the desired properties of a tracer. It is inert, relatively non-toxic, colorless, odorless, tasteless, non-flammable, non-corrosive and thermally stable. It is not a normal background constituent of air. The six fluoride atoms in the molecule make the compound extremely sensitive to an electron capture detector.

There are certain problems which must be considered when using SF_6 as a tracer. The detector unit may require frequent calibration to maintain the desired accuracy. Also, because of the high sensitivity of the detector, minor leaks in regulators, valves and connections, which would go unnoticed in other gas measurement systems, are completely unacceptable when SF_6 is used as an indoor tracer. The measurements are in the form of chromatographic peaks which may require special equipment for automation and data processing.

AN AUTOMATED SYSTEM FOR MEASURING AIR INFILTRATION

The air infiltration measuring system is made up of three subsystems, as follows:

1) the programmable calculator,
2) the SF_6 discharge system,
3) the SF_6 measuring system.

The SF_6 discharge system and the SF_6 measuring system are controlled by the INPUT and OUTPUT instruction of the calculator. The control logic for both systems is housed in the unit named "INTERFACE", developed at the Division of Building Research (Fig.1).

(1) The Programmable Calculator

The Hewlett Packard 9815A is a desk-top programmable calculator. It features a built-in, high speed magnetic tape recorder that uses a data cartridge, a 16-character alphanumeric thermal printer, an auto-start switch, programming keys that double as special function keys, and two optional I/O channels.

The 9815A is used with a Hewlett Packard (HP) 98133A Binary-Coded Decimal

(B.C.D.) and an HP 98135A Interface Bus (IB). The B.C.D. interface connects the calculator to the DBR "INTERFACE" and the IB interface connects the calculator to the HP59309A ASCII digital clock.

(2) The SF_6 Discharge System

The discharge of SF_6 is controlled by two solenoid operated gas valves connected in series, as shown in Fig. 2. These two valves are normally closed. The volume of SF_6 to be discharged is trapped between two valves, D_1 and D_2. When the calculator requests a discharge, Valve D_1 opens for 0.1 sec, allowing the SF_6 between D_1 and D_2 to escape. After 0.1 sec, valve D_1 is closed, and both valves remain closed for the next 0.1 second. Valve D_2 is then opened for 0.1 sec. This allows SF_6 to fill the volume between valves D_1 and D_2. The discharge system is now recharged and is ready for the next discharge request.

The timing of the discharge sequence is controlled by a simple circuit. The SF_6 discharge sequence is always under control of the calculator OUTPUT instruction which can be triggered by the operator through the calculator keyboard or by the OUTPUT instruction itself.

There are two modes of control. One mode triggers the discharge sequence directly by outputting two control words in sequence. Each time the two output words are used, one volume of SF_6 is discharged. This discharge can be repeated every 0.9 sec. This mode can be used either for the constant concentration or the decay method.

The second mode controls the time interval between the automatic discharge of one volume of SF_6. This mode uses the calculator output word to program an interval timer, which triggers the discharge sequence circuit. The basic time interval is selected by the operator. The calculator output word can then multiply this time interval from 1 to 31 times, or stop the discharge altogether. This mode can be used for the decay method only.

(3) The SF_6 Measuring System

a) General Description of the System. The SF_6 measuring system is made up of four major components, as follows:

- i) The Ion Track Instruments Incorporated SF_6-Detector/ Chromatograph, used as a gas chromatograph and detector unit;
- ii) A Newport 2000B/S-1 Digital Panel Meter with a voltage of 1.9999 VDC;
- iii) Part of the "INTERFACE";
- iv) An electro-pneumatic operated sample valve which replaces the sample valve of the chromatograph.

The SF_6 measuring system has two modes of operation. One mode used the calculator OUTPUT instruction to take a reading of the SF_6 concentration. This mode can be used either for the constant concentration or the decay method. The other mode is not under the control of the calculator. An interval timer in the "INTERFACE" is used to trigger the SF_6 measuring system. Time intervals from 1 to 15 min are available in 1-min steps. This mode can only be used for the decay method.

b) Operation of SF_6 Measuring System. The operation of the SF_6 measuring system is described, with reference to Fig. 3. The detector/chromatograph, as supplied, is manually operated. The system is automated by replacing the manually operated sample valve by an electro-pneumatically operated valve.

When the SF_6 measuring system is triggered by a calculator OUTPUT instruction, or by the internal interval timer, the sample valve control circuit operates the sample valve for 5 sec. The analogue output of the chromatograph, after the sample valve is operated, is shown in Fig. 4. The first peak represents the O_2 concentration reading and the second peak represents the SF_6 concentration.

The analogue output is digitized by a Newport digital panel meter. This digitized chromatograph output is made available to the calculator by the use of a READ instruction in the calculator.

The digitized chromatograph output is also made available to the auto SF_6 peak finding ciruit. This circuit allows the calculator program to identify O_2 or SF_6 outputs of the chromatograph. This is done by changing the polarity of the data as seen by the calculator. All the digitized readings, from the time of the sample valve operation until the start of the SF_6 peak, are made to have a negative polarity. The start of the SF_6 peak changes the polarity of the readings, as seen by the calculator, to a positive value. The calculator can be programmed to look for positive readings and, in this way, can identify the SF_6 data.

The system is intended to be used for unattended operation. In the case of a power interruption, all the AC output control circuits are deactivated and must be manually reset to bring them back into operation.

INSTRUMENT CALIBRATION

(1) Laboratory Test

To determine the accuracy of the SF_6-detector/chromatograph, as employed in the tracer gas technique, tests were conducted with a glass tank having a volume of 0.0177 m^3. A small fan was provided inside the tank for mixing air and tracer gas. A controlled rate of air, from a service line, was piped to an opening in the tank to obtain a predetermined rate of air input to the enclosure. SF_6/air mixture in the tank was allowed to leak out through a rubber tube connected to the tank. Both the constant concentration and decay methods were checked by this system. The schematic diagram of the experimental set-up is shown in Fig. 5.

Tests were conducted with different air flow rates of 0.2 to 9 air changes/hr. The results of these tests are shown in Fig. 6. The coefficient of correlation was found to be 0.99742 for the decay method, and 0.99671 for the constant concentration method. The average error was found to be only 1.5% for both methods.

It was evident from the tests that care should be taken how best to process field data. Tests have shown that changes in the sensitivity of the detector to SF_6 concentrations do occur. This is especially true in the warm-up period of the SF_6-detector/chromatograph. It can be avoided by starting the equipment half an hour before the test.

The tests have shown that the SF_6-detector/chromatograph, as used in the automated system, gives reliable results.

(2) Field Test

The air infiltration measurement system was tested in a 3-bedroom, experimental energy conservation house in Regina, Canada, using both the decay and the constant concentration methods.

For the decay method, SF_6 was introduced automatically into the furnace air recirculation fan at a selected SF_6 concentration level, and the build-up and decay of tracer in the house was measured from the sample extracted from the return air duct. For the constant concentration method, tracer gas was injected downstream of the furnace fan, and the sampling was done ahead of the fan. In both tests, the data were recorded on the magnetic tape cassette of the HP9815 calculator, and played back or printed on thermal printer paper.

The furnace fan was operated continuously during the experiment to achieve good mixing. Samples were taken from the return duct every 2 min. Several tests were conducted to check the reliability of the system. The results of one 2-hr test of the decay and constant concentration methods are plotted in Fig. 7. The agreement between these two methods is within normal experimental error. The computed values of air change rate per hour for the decay and constant concentration methods were found to be 0.615 and 0.608, respectively. In several other tests, the results of the two methods agreed within 2%.

Tests were also conducted using the pressurization method, along with the decay method in a 2-story, 3-bedroom house located in Ottawa, Canada.

For the pressurization method, the air was exhausted from the house with a centrifugal fan and the drop in the inside pressure and, simultaneously, the air flow rate through the fan duct were measured with a laminar flow element. A detailed description of the experimental procedure is reported by Tamura (5). Several tracer gas tests using the constant concentration and decay methods were conducted at different air flow rates of 0.5 to 1.6 air changes/hr. The level of tracer gas concentration during the tests using the constant concentration method was maintained between 5 ppb to 20 ppb. Pressure difference across the walls of the house was also measured at 2 locations on each wall and across the ceiling of the 2nd floor to ensure that the direction of flow through the house enclosure was the same everywhere during the test conducted under moderate wind.

The furnace fan, of 0.436 m3/sec (4 air changes/hr) capacity, was operated continuously during the experiment to achieve good mixing. The results of pressurization and constant concentration measurements are plotted in Fig. 8, and the results of pressurization and decay measurements are plotted in Fig. 9. The average error was found to be only 5% for both methods.

The system operated satisfactorily for about 6 hr, but beyond this period a slight zero shift of the instrument occurred (less than 4%) which can be corrected simply by resetting the zero adjustment knob of the SF_6-detector/chromatograph. This problem has since been overcome by a change in the program to read and correct for the zero shift.

CONCLUSIONS

An automated system to measure air infiltration rates in buildings, using SF_6 as a tracer gas, was developed and checked both in the laboratory and in the field. It is made up of 3 main subsystems - the programmable calculator, the SF_6 discharge system, and the SF_6 measuring system. Concentration levels of SF_6 are maintained at the parts per billion level in the buildings, and are measured by a sensitive electron capture detector in conjunction with a gas chromatograph.

The system can be operated using either the decay or the constant concentration method. Air infiltration measurements in the laboratory and the field by both methods showed that the average error is only 1.5%. Repeated 6-hr-long, unattended operation has been achieved by both methods. Field tests in a house with the pressurization and tracer methods showed only 5% error in the air infiltration measurement results.

The conclusions on the automated air infiltration measuring system, laboratory and field calibration and operation from an instrument standpoint, have been favorable.

REFERENCES

1. ASHRAE Handbook and Product Directory, 1977 Fundamentals Volume, ASHRAE, Inc., New York, N.Y.
2. C.M. Hunt, D.M. Burch, "Air Infiltration Measurements in a Four Bedroom Townhouse Using Sulphur Hexafluoride as a Tracer Gas," ASHRAE Trans. Vol. 81, Part 1, p. 186, (1975).
3. G.F. Collins, F.E. Bartlett, A. Turk, S.M. Edmonds and H.L. Mark, "A Preliminary Evaluation of Gas Air Tracers," J. Poll. Cont. Assoc., 15, p. 109, (1965).
4. H.W. Orr, "Studies and Improvements to an Air-Infiltration Instrument," M.Sc. Thesis, University of Saskatchewan (1963).
5. G.T. Tamura, "Measurement of Air Leakage Characteristics of House Enclosures ASHRAE Trans., Vol. 81, Part 1, p. 202, (1975).

ACKNOWLEDGEMENTS

The authors wish to record their appreciation f the help of their colleagues, Dr. C.P. Hedlin, S.S. Tao and R.G. Nicholson, of the Prairie Regional Station of the Division of Building Research, during the investigation. The authors also wish to acknowledge the contribution made by G.T. Tamura, R.G. Evans and R. Plouffe, of the Energy and Services Section, during the tests conducted in Ottawa.

The work was carried out as part of the research program of the Division of Building Research, National Research Council of Canada.

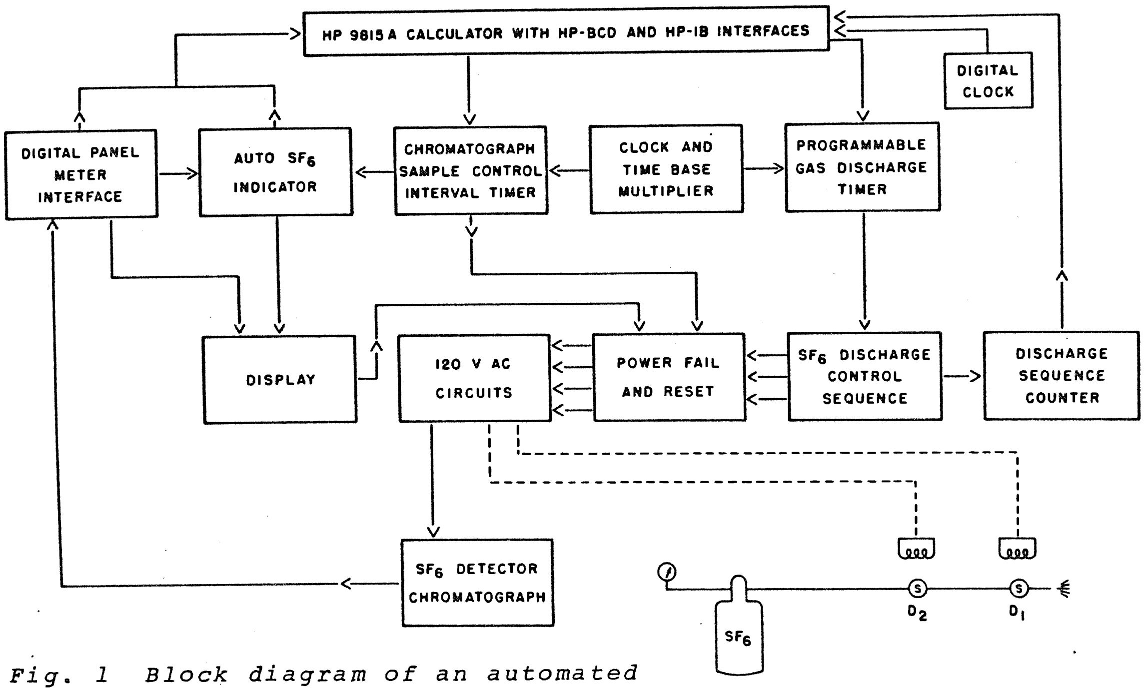
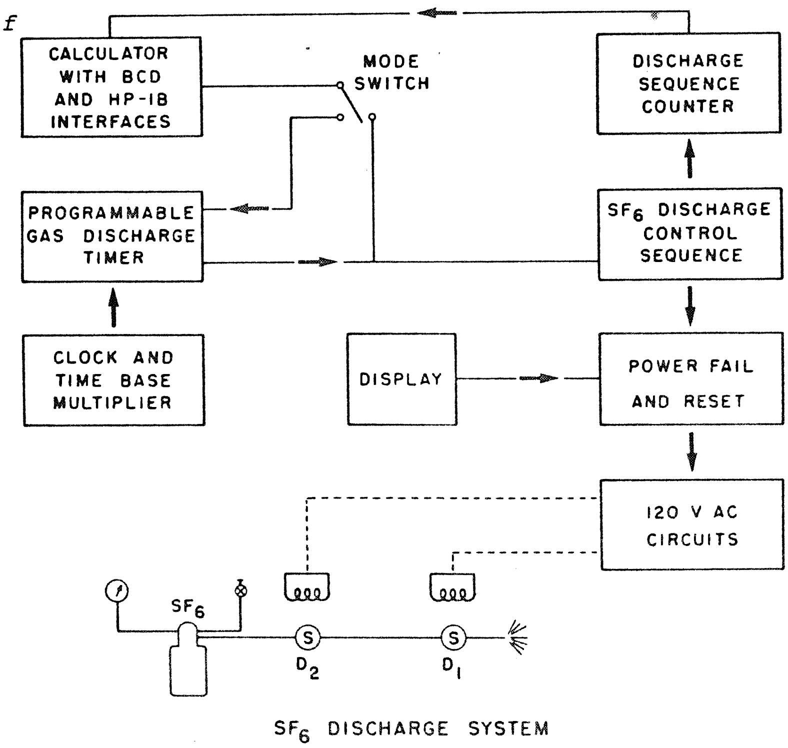


Fig. 1 Block diagram of an automated system for measuring air infiltration

Fig. 2 Block diagram of SF_6 discharge system



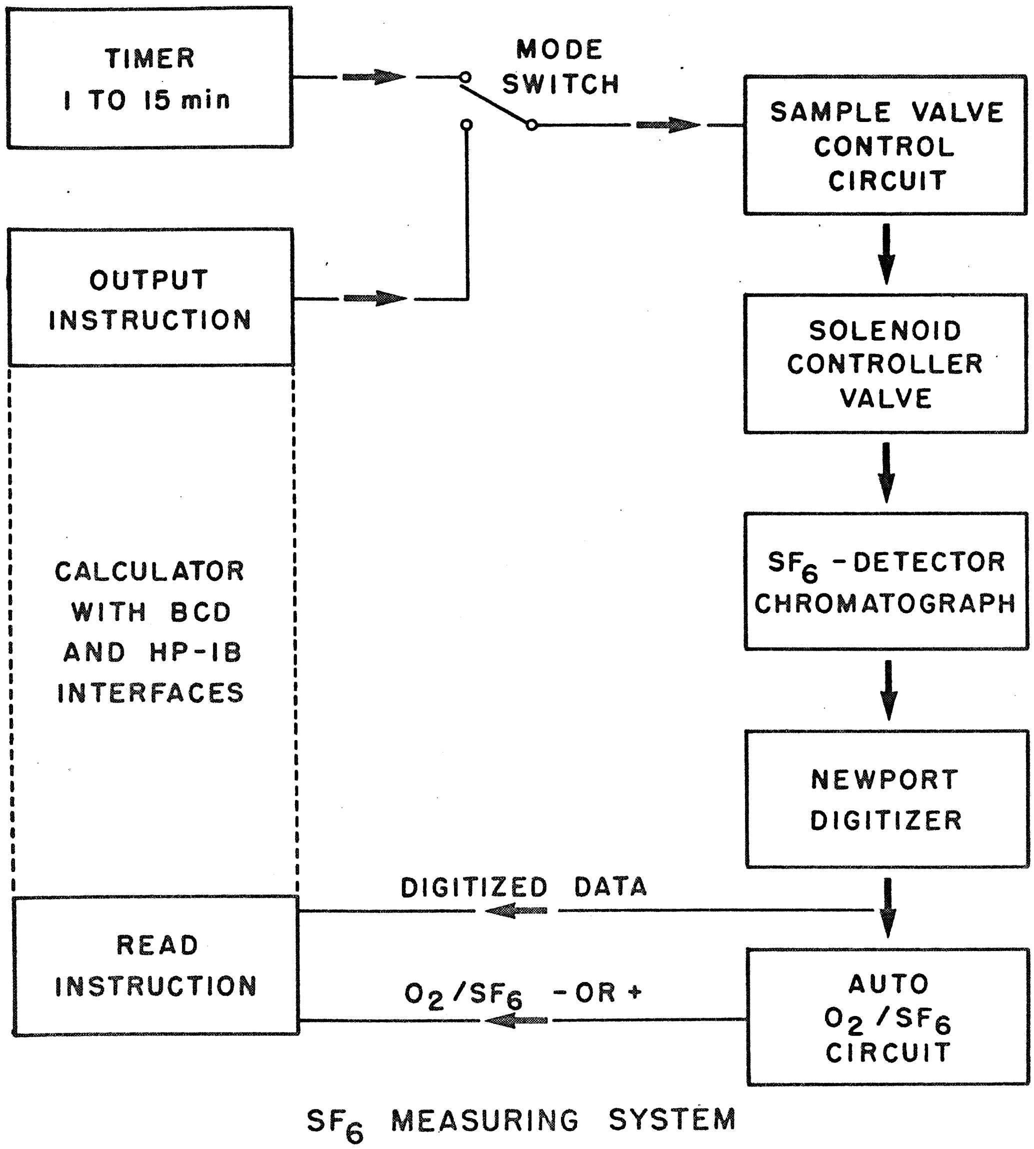
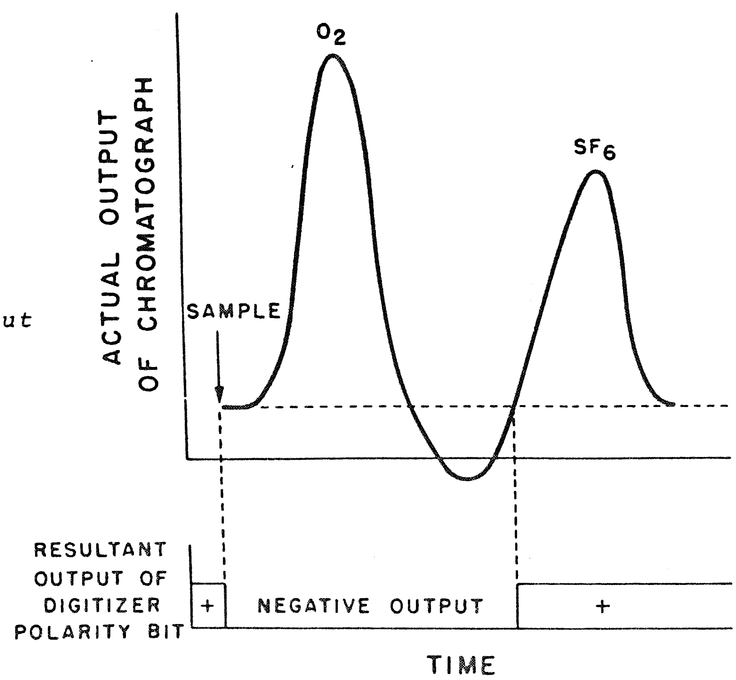


Fig. 3 Block diagram of SF_6 measuring system

Fig. 4 Analogue output of chromatograph



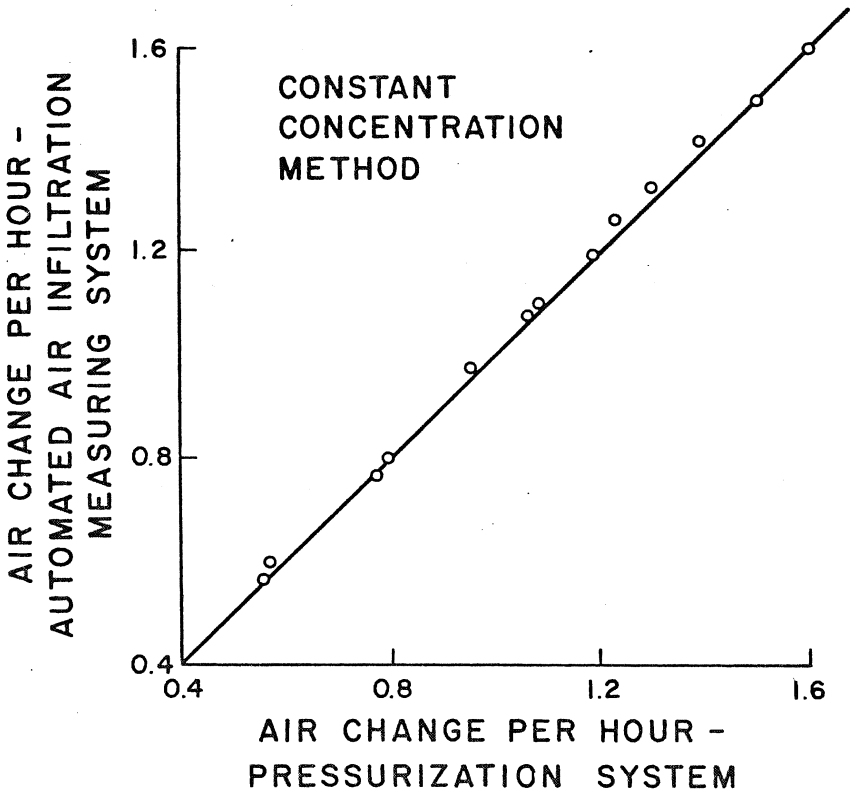


Fig. 8 Calibration tests on an automated air infiltration measuring system using SF_6 Tracer gas - Constant Concentration Method

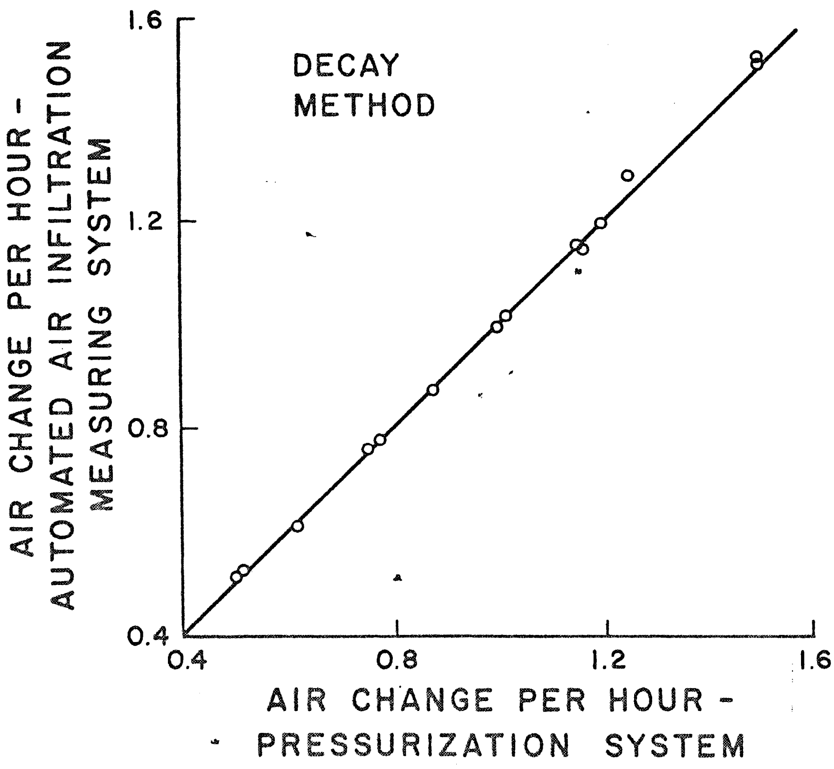


Fig. 9 Calibration tests on an automated air infiltration measuring system using SF_6 Tracer gas - Decay Method

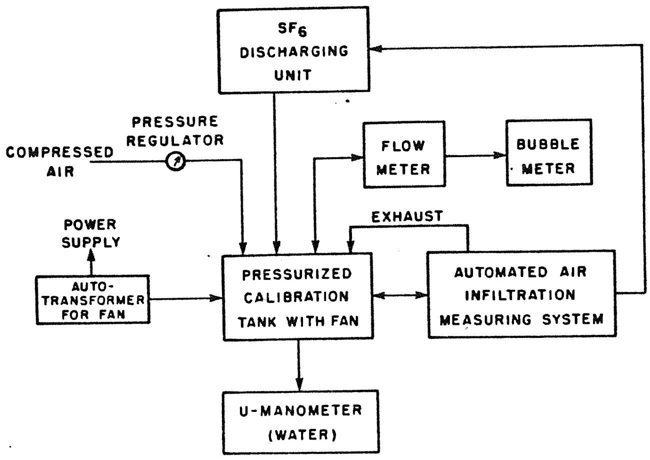


Fig. 5 Block diagram showing instruments used for calibration of an automated system for measuring air infiltration

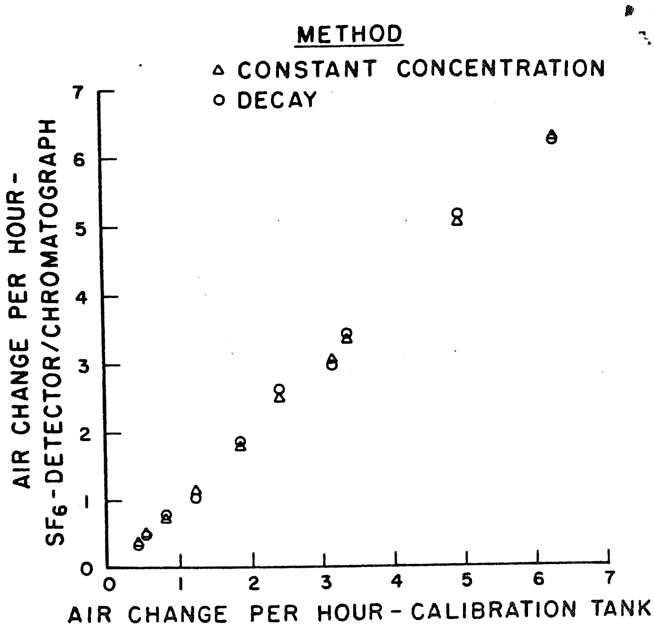


Fig. 6 Calibration tests on SF_6-detector/chromatograph

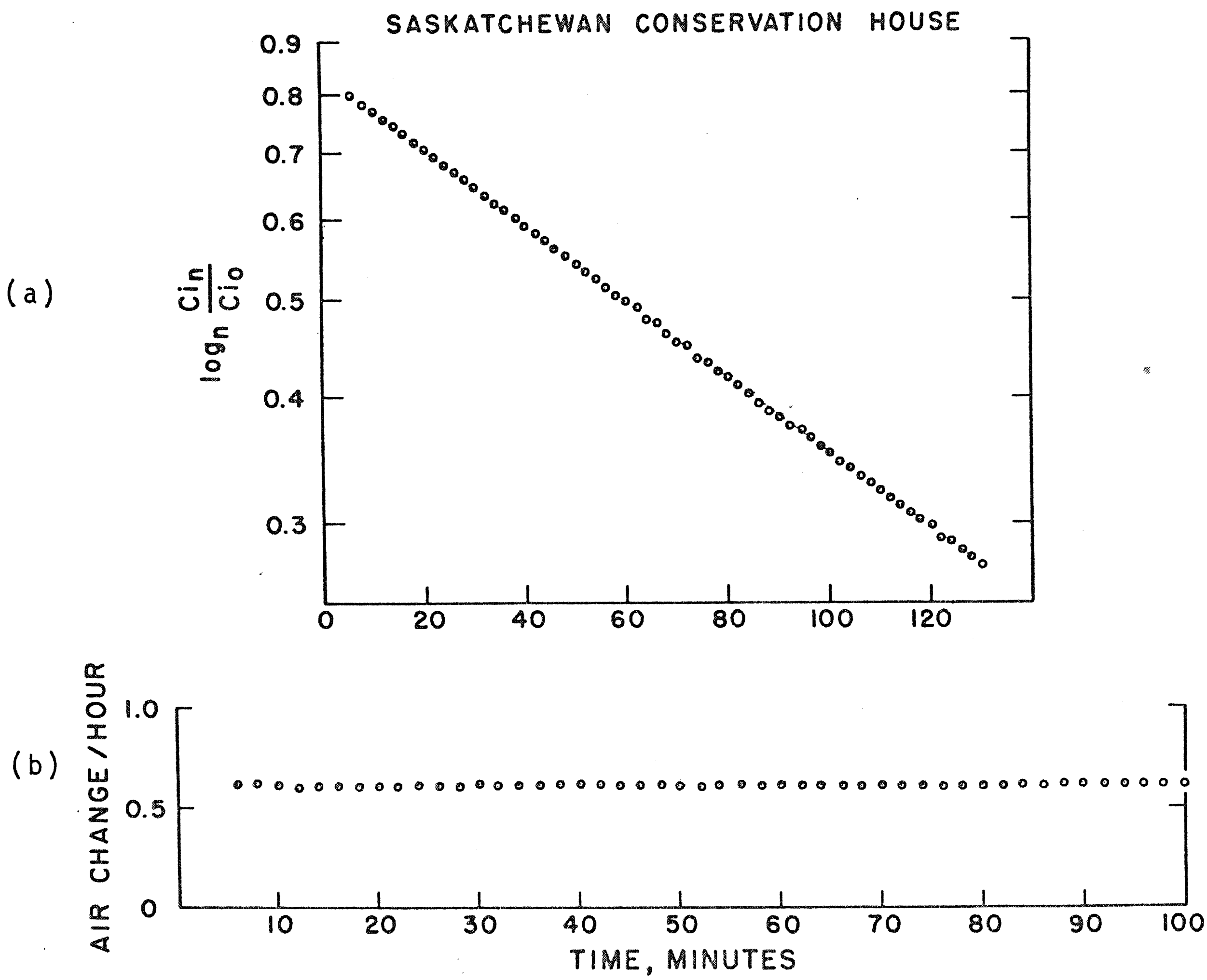


Fig. 7 Typical printout of magnetic cassette of air infiltration vs time: (a) Decay Method; (b) Constant Concentration Method