HI-85-40 No. 3

Documenting Air Movements and Infiltration in Multicell Buildings Using Various Tracer-Gas Techniques

D.T. Harrje, Ph.D. *ASHRAE Member*
G.S. Dutt
D.L. Bohac *ASHRAE Student Member*
K.J. Gadsby

ABSTRACT

Tracer gas techniques for measuring airflows in buildings fall into three categories -- dilution, constant injection, and constant concentration. Dilution of a single tracer works well in buildings with a single zone and also in some two-zone buildings. Multiple tracer gas measurements, necessary to characterize flows among more zones, are best conducted using the constant injection approach. The constant concentration method uses a single tracer gas to determine the air flow rates from the outside into each of as many as ten building zones.

The paper outlines the different tracer techniques for making airflow measurements in multicell buildings and describes the operation of a constant concentration system. This system measures tracer gas concentration in different zones and injects accordingly to maintain a constant concentration in each zone. The system was tested in a single zone structure and successfully applied to a small three-zone house. Sensitivity analyses and calibration procedures described in this paper define the capabilities and limitations of this technique. Although this method does not fully characterize all interzone airflows in the building, it can be useful in analyzing the energy balance of multizone buildings. Additionally, these measurements can be used to evaluate the dilution of indoor air pollutants and the ventilation efficiency of buildings.

INTRODUCTION

The past decade has seen the development of many techniques utilizing tracer gases for measuring air infiltration, ventilation, and airflow within buildings (Liddament et al. 1983). These range from measurements of air infiltration rate where the building is treated as a single uniformly mixed zone to more complex measurement techniques that treat the building as several coupled zones exchanging air with one another and with the outside. Furthermore, some techniques give airflow rates averaged over short time intervals, while others directly yield values averaged over extensive periods of time -- from days to many weeks.

The various methods may be grouped into the following categories -- tracer gas dilution, constant injection of tracer gas, and maintaining a constant concentration of tracer gas. One or more tracer gases may be used.

The most common approach for measuring air infiltration in buildings uses the dilution or decay of a single tracer gas. This method assumes that the building interior can be treated as a single uniformly mixed space within which the tracer gas concentration is everywhere the same. A small quantity of a single tracer gas is injected into the building. As outside air leaks into the building, the tracer gas concentration in the building air falls. The building's average air infiltration rate is determined from periodic measurements of the tracer gas concentration within the building.

D.T. Harrje is a Senior Research Engineer, G.S. Dutt is a Research Engineer, D.L. Bohac is a Graduate Student and K.J. Gadsby is a Technical Associate in the Center for Energy and Environmental Studies at Princeton University, Princeton, NJ 08544.

The tracer gas decay technique does not tell us the airflows in a building that cannot be treated as a single uniformly mixed zone. These include large buildings lacking a single air-circulation system. Even for houses, we cannot reliably determine the air infiltration rate if there is no forced air heating or central air conditioning system and where the interior doors are kept closed.

The single tracer decay method can, however, be adapted to a building made up of two zones, each of which may be treated as uniformly mixed. In this case, the tracer gas is injected into one of the two zones and the concentration of the tracer gas is monitored in both zones. The airflow rates among the two zones and the outside can be calculated from the concentration measurements.

One important limitation of the tracer gas decay technique is that it yields a measurement only for a certain time interval following injection while the tracer gas concentration is large enough to be reliably measured. Two ways of getting around this problem have been developed. In one approach, an automated system repeats the injection at regular intervals. Air samples are also automatically collected, analyzed, and recorded at regular intervals to determine the air infiltration rate variation over extended periods of time (Harrje et al. 1975, Grot et al. 1980).

In another approach, the tracer gas is injected continuously at a constant rate (the constant injection method). Periodic sampling, analysis, and automatic recording of tracer gas concentration permits measurements of long-term variations in air infiltration (Condan et al. 1980). Alternative methods, discussed later, permit the measurement of long-term average average infiltration rates directly (Dietz et al. 1982).

The constant concentration technique permits the determination of many more flow rates in a multizone building, still using a single tracer gas. In this method, the tracer gas concentration is measured at frequent intervals in each of the zones. Based on these measurements, a certain measured quantity of tracer gas is injected into each zone so that the concentration in each zone remains essentially constant. The air flowing from the outside into each of the zones is calculated from measurements of the amount of tracer gas injected into that zone. This approach has been successfully used in buildings with as many as ten zones in Canada, (Kumar et al. 1979), Denmark (Collet 1981), Sweden (Lundin et al. 1983), the United Kingdom (Alexander et al. 1980), and the United States.

However, even the most sophisticated single tracer gas technique does not tell us all the flow rates of interest in buildings with more than two zones. The simultaneous use of multiple tracer gases is needed for additional information (Sinden 1978). The number of zones among which airflows can be fully documented is limited by the number of different tracer gases available. At present, up to four different tracer gases have been used (I'anson et al. 1982).

Multiple tracer gases, like single tracer gases, can be used in the decay and constant injection modes. Using the decay mode tends to be analytically cumbersome, (Sinden 1978), as we shall see, and researchers currently favor the constant injection technique (Dietz et al. 1984, Harrje et al. 1981).

Single Tracer, Single Chamber Measurement

The simplest experimental method is the single chamber decay of a single tracer gas. A certain quantity of the tracer gas is introduced into the air and allowed to mix so that the concentration becomes uniform throughout the space. Samples of air are taken periodically and analyzed. The concentration of tracer gas is measured. As outside air containing no tracer gas enters the building, the concentration shows an exponential decay:

$$C = C_o \exp(-k\ t) \tag{1}$$

Taking the natural logarithms of both sides, we have:

$$\ln(C) = A - k\ t \tag{2}$$

where

$$A = \ln(C_o)$$

The downward slope, k, of the graph of ln (C) vs. time t is the air-infiltration rate. The volume flow of air in and out of the building is given by $Q = V\ k$, where V is the building interior volume.

The single tracer decay requires that the tracer be injected into a uniformly mixed zone. The mixing is frequently enhanced by operating circulation fans such as a furnace fan or by special mixing fans. However, even without any mechanical mixing system, the method gives reliable values of the spatially averaged air infiltration rate for houses and other small buildings.

When initially developed, the tracer decay method required the detection unit to be located in the building being monitored. Since then, bottle and bag sampling techniques have been developed that permit measurements without the presence of the detector on site (Harrje et al. 1981, Grot 1980, Harrje et al. 1982). A small quantity of the tracer gas is carried to the site in a plastic bottle or bag and released into the building by opening the bottle. Subsequently, several air samples are collected from the building using other plastic bags or bottles. The containers are sealed after sampling and the sampling times noted; containers are later analyzed using equipment located in the laboratory. This technique has worked well with sulfur hexafluoride tracer gas, which is analyzed using a gas chromatograph equipped with an electron capture detector. This type of detector requires relatively small air-flows during analysis. Gases detected using an infrared absorption technique may not be suitable for container sampling because of the large flow rates involved during analysis.

Single Tracer, Two-Chamber Measurement

Although the average air infiltration rate of a house can be measured using a single tracer gas decay, multizone measurements are essential to correctly represent the movement of indoor air contaminants and moisture among different spaces within a house. For instance, the radioactive gas radon typically originates from the soil under the house and is released primarily into the basement or crawl space of the house. The concentration in the living space depends on the source strength of radon in the basement as well as the airflows among the basement, living space, and the outside. Hernandez used two-zone flow measurements to determine radon flux balances in several test houses with large radon sources (Hernandez et al. 1982). The single tracer gas injection and decay method can be adapted to the measurement of airflows in a two-zone building (Sinden 1978, Hernandez et al. 1982). The tracer gas is injected into one zone and air samples from both zones are collected and analyzed periodically. In the injected zone, the tracer gas concentration falls off rapidly at first and then more slowly, while the concentration in the other zone increases at first and then falls off.

The concentrations of tracer gas in the injected zone (i) and the other, alternate, zone (a) are given by the following equations:

$$C_i\ (t) = a_{11}\ e^{k_1 t} + a_{12}\ e^{k_2 t} \qquad (3)$$

(3)

$$C_a\ (t) = a_{21}\ e^{k_1 t} + a_{22}\ e^{k_2 t} \qquad (4)$$

where C_i and C_a are the tracer gas concentrations in the injected and alternate chambers; k_1 and k_2 are two time constants that characterize the airflows among the two chambers and the outside; the four constants a_{11}, a_{12}, a_{21}, and a_{22} incorporate the initial conditions of the injection (Sinden 1978, Hernandez et al. 1982).

Two quantities r_1 and r_2 are defined for convenience as follows:

$$r_1 = \frac{a_{11}}{a_{21}}, \quad \text{and} \quad r_2 = \frac{a_{12}}{a_{22}} \qquad (5a,b)$$

Once the values of k_1, k_2, r_1, and r_2 are known, the flow parameters can be readily determined. Sinden proposed two methods for calculating the values of these constants from measurements of tracer gas concentrations (Sinden 1978). One of these methods is a statistical procedure that utilizes all of the observations and is therefore likely to be more reliable.

Equations 3 and 4 are rewritten as:

$$y_1 (t) = \ln [C_i (t) - r_1 C_a (t)] = \ln [a_{12} - r_1 a_{22}] + k_1 t \tag{6}$$

$$y_2 (t) = \ln [C_i (t) - r_2 C_a (t)] = \ln [a_{11} - r_2 a_{21}] + k_2 t \tag{7}$$

Sinden recommended regressing the y values against time for various r values; the best fit is used to estimate r and k values. The method involves iterative regressions.

Hernandez proposed an alternative calculation procedure. He divided the data into two time intervals -- a transient period and a dominant period. During the dominant period, the shorter time constant of the system has died out, and concentrations in both chambers decay at the same rate. Graphs of ln (C_a) and ln (C_i) against time are parallel. He used the dominant period to first calculate the longer time constant and two of the four "a" coefficients. These values were then substituted into Equations 3 and 4 and a simpler, noniterative, regression of concentration data from the transient phase was used to determine the remaining parameters (Hernandez et al. 1982).

The six sets of flow rates connecting the two chambers and the outside are given by:

$$F_{ia} = V_a (k_2 - k_1) / (r_2 - r_1) \tag{8}$$

$$F_{ai} = V_i (k_2 - k_1) r_1 r_2 / (r_1 - r_2) \tag{9}$$

$$F_{oa} = V_a [k_2 (r_1 - 1) - k_1 (r_2 - 1)] / (r_2 - r_1) \tag{10}$$

$$F_{oi} = V_i [k_2 (1 - r_1) - k_1 (1 - r_2)] / (r_2 - r_1) \tag{11}$$

$$F_{io} = F_{oi} + F_{ai} - F_{ia} \tag{12}$$

$$F_{ao} = F_{oa} + F_{ia} - F_{ai} \tag{13}$$

where V_a, V_i are the volumes of the alternate and injected zones, and F_{ij} is the flow rate from zone i to zone j. Hernandez used his method to determine the flows for two relatively well-coupled zones -- the living space and basement of a house (Hernandez et al. 1982). For the well-coupled case, the method works relatively well. Figure 1 shows sulfur hexafluoride tracer gas concentration in the living space and the basement of a Princeton house, following injection into the basement.

Ford has also used the method to measure flows between the living space and the attic of a house, two zones usually poorly coupled. Here the method encounters some difficulties (Ford 1982). The main problem arises from the limitation in range of the equipment used to detect the tracer gas. For instance, when tracer gas is injected into the living space of a house, the concentrations in the attic are much smaller because the air exchange between the living space and the attic is small compared to airflows among different zones within the living space, or between the living space and the basement. Also, attics are vented and this too reduces the tracer gas concentration there. If the injection in the living space is within the measurement range of the detector, the attic concentrations are likely to be too small to be reliably measured. Alternatively, if enough gas is injected into the living space for the concentration in the attic to be measurable, the concentration in the living space is likely to saturate the detector. We have so far been unsuccessful in making reliable measurements of airflows between the living space and the attic using the tracer decay method. At present our sulfur hexafluoride detector can be used for concentrations in the range of 20 to 500 parts per billion (ppb). What is needed is a detector that can measure concentrations over a very wide range of values.

Another problem with the use of a single injection of a tracer gas in a two-zone airflow measurement arises irrespective of the coupling between the chambers. In order to make reliable parameter estimates, the measurements need to be continued until the transient phase has been replaced by the dominant phase. In some cases this has taken ten hours or more. The duration of the measurement poses several problems. First, the concentrations in one or both chambers may fall to such a small value that it becomes undetectable before the measurement is over. Second, the mathematical formulation assumes that the flow rates remain constant. For a long measurement period, this assumption is unlikely to hold. Single-zone tracer gas decay experiments often show air infiltration rate variations of a factor of three during the course of a single day.

A single injection of tracer gas to provide a uniform initial concentration in each zone, followed by dilution has been used by Sandberg to determine a "ventilation efficiency" for a multizone building (Sandberg 1981, Freeman et al. 1982). This technique cannot, however, be used to determine the rates of outside airflow into each zone; nor can it be used to determine changes in ventilation rate over time without an elaborate, automated reinjection and mixing setup to regain uniform concentrations in all spaces.

Constant Injection Systems

Some of the problems of the tracer decay measurements can be overcome using a constant injection approach. Here, continued injection permits the concentration of the tracer gas to be kept within the range of the detector. Lawrence Berkeley Laboratory researchers have used the constant injection method to advantage (Condon et al. 1980).

One of the most interesting applications of the constant injection arises in the combination of a passive constant injection source and a passive sampler developed by Dietz et al. at Brookhaven National Laboratory (Dietz et al. 1982, Dietz et al. 1984). In their method, a bullet-sized canister closed by a rubber stopper passively releases a perfluorocarbon tracer gas into the building at a nearly constant rate. (The source emission is, in fact, temperature-dependent. However, since interior temperatures of occupied buildings do not vary much, the variation in tracer emission is small. The average rate of release of tracer can be calculated from measurements of the interior temperature.) Diffusion tube sampler(s) passively collect tracer gas from the air in the building over long periods of time. Later analysis of the samplers yields the building's long term average air infiltration rate for the sampling duration. This method's chief attraction is that it can be used to inexpensively measure the long-term average air-infiltration rate. The Brookhaven method is adaptable to multiple tracer gases and therefore suitable for multizone airflow measurements. Several different tracer sources and samplers are located in the building. Each sampler is later analyzed for each tracer. Brookhaven has successfully used up to four different tracers and measured airflows among living space, basement, and attic of a house (Dietz et al. 1984).

Other constant injection methods require that the expensive, automated equipment left in the building for long periods of time function reliably and, moreover, requires extensive data analysis to determine average infiltration rates.

Constant Concentration Systems

It is often necessary to know the level of air infiltration into each zone of a building, for instance, in order to determine if all parts of a building are being ventilated adequately. The constant concentration system permits this measurement to be made by keeping the tracer gas concentration constant in each zone and uniform throughout the building. For each zone j of a building, the multizone flow equations are given by:

$$V_j \frac{dC_j}{dt} = -C_j F_{ji} + C_k F_{kj} + S_j \qquad (14)$$

where

V_j = volume of zone j

F_{ji} = airflow from zone j to zone i

C_j = tracer gas concentration in zone j

S_j = rate of tracer gas injection into zone j

This set of equations is greatly simplified in the case where the tracer gas concentrations in all zones are equal and constant. In such a case, C_j is the same for all j and equal to C_d, the desired steady concentration. For an appropriate choice of tracer gas, its concentration outside C_o is 0 and dC_j/dt is also 0, so that the equations reduce to:

$$F_{oj} = \frac{S_j}{C_d} \tag{15}$$

where F_{oj} is the airflow from outside to zone j. Thus, by holding the concentration constant, the infiltration into a zone is simply the tracer injection rate into the zone divided by the steady concentration.

In order to keep the concentration steady, the system must be able to sample the air and measure the tracer gas concentration in each zone, calculate the rate of tracer gas injection needed for each zone given the measured concentration, and inject the tracer gas at a variable rate into each zone -- all on a time scale that will allow adequate control of the concentration in each zone. Ideally, we would like an instantaneous measurement of tracer gas concentration in each zone and continually vary the injection into each zone. In practice, several factors prevent such instantaneous measurement. However, the airflow rates change slowly enough that measuring the concentration in fairly large discrete steps and using a constant flow, adjustable on-time injection system provides adequate control.

Our system operates on a 60 second cycle during which the following operations take place:

1) concentration of a zone is measured

2) sample valve of the next zone is opened

3) injection rate of the measured zone is calculated

4) new information is displayed on monitor and saved to disk storage

5) tracer gas is injected into all zones

After the cycle is complete, the operations are repeated on the next zone. The number of minutes between measurements in a zone is equal to the total number of zones, i.e., with ten zones there is a ten-minute interval.

Our system consists of an electron capture gas chromatograph, a series of ten sample and injection lines, an auxiliary pump, and a microcomputer-based measurement and control system (see Figure 2). The auxiliary pump purges the sample lines when they are not connected to the detector. The volume of gas injected in a cycle is controlled by opening a valve to a constant flow nozzle for a specified length of time. The drawback to this system is that the range of volumes that can be released is limited on the low end by the accuracy of the known volume injected at small open times, and on the high end by the length of time in the cycle in which injection can take place. This range is approximately 0.5 to 30 seconds. Due to this limitation, the steady concentration must be carefully chosen so that the open time will fall within the allowable range for each of the zones and a wide range of infiltration rates. The following equation is used to specify the steady concentration:

$$\text{steady conc.} = \frac{(\text{nozzle flow rate})\,(\text{conc. of injected } SF_6)}{(\text{estimated } F_{oj})\,(\text{cycle time/valve open time})} \tag{16}$$

Choosing a valve open time of 3.9 seconds will allow infiltration rate measurements that are a factor of four above or below the initial guess of F_{oj} used in Equation 16, while allowing for a factor of two fluctuations in the injection rate. The flow rate of each nozzle is adjusted to compensate for different zone volumes. Given a zone volume of 100 m^3, a valve flow rate of 5 cc/sec, and a concentration of injected SF_6 of 0.7%, air infiltration rates from 0.08 to 1.2 changes per hour can be measured with a steady concentration of 275 ppb. Buildings with larger zones are accommodated by increasing the concentration of the injected SF_6.

All constant concentration systems use some form of a proportional-integral-differential (PID) control algorithm to calculate the injection rate. The quantity of tracer gas injected is given by the sum of three terms:

$$S_j = \overset{\text{proportional}}{A (C_d - C_m)} + \overset{\text{integral}}{F_{oj} C_d} + \overset{\text{differential}}{D (C_p - C_m)} \tag{17}$$

where

C_m = present measured concentration

C_p = concentration measured in previous cycle

A = proportional constant

D = damping constant

D = 0 if $\mathrm{abs}(C_p - C_d) > \mathrm{abs}(C_m - C_d)$

The proportional term provides a correction based on the difference between the present measured concentration and the desired concentration, the integral term compensates for the depletion due to outside air infiltration, and the differential term damps the change in concentration towards the desired value. Our PID algorithm, similar to one developed in Denmark (Collet 1981), incorporates all three terms. The constant A is chosen so that the difference between the present and desired concentration is made up in 20 minutes, D provides enough correction so that the amount the concentration moved away from the previous sample is made up in 10 minutes.

In the absence of elements causing the system to be potentially unstable -- such as noninstantaneous mixing of injected SF6, incomplete mixing of outside air with room air, and concentration measurement errors -- the value of F_{oj} calculated from the previous cycle could be used in the control algorithm. In order to add stability to the system, F_{oj} is averaged over a longer period of time -- longer time periods produce more damping but increase the response time to changes in infiltration flow rates. Our experience thus far indicates that averaging F_{oj} over one hour provides a good compromise. As our single-zone test shows (Figure 3), the system is able to respond to a change in the air-infiltration rate (AIR, the flow rate of outside air into the zone expressed as zone volumes per hour) from 0.28 to 0.48 that occurs over 2.5 hours without a significant deviation of the tracer gas concentration from its steady value.

Other steps are taken to reduce the oscillations of the concentration caused by instabilities and to measure zone infiltration flows more accurately. Small fans are placed in each zone to improve mixing. The outlet of the injection line is placed downstream of the fan and the inlet to the sample line is placed upstream. With this arrangement, the injected gas completes a loop of the zone, mixing with the room air and incoming outdoor air before it has a chance to enter the sample line. Another contributing factor to oscillatory system behavior is detector measurement error. For typical air-infiltration rates, the proportional term in the control reacts strongly to small changes in concentration. A measured concentration that is smaller than the real value will cause the injection rate to increase, which also causes the calculated AIR for the next cycle to increase somewhat. If the AIR remains constant, the concentration will increase above the steady value. The system responds by decreasing the injection rate so that the concentration will settle down to the steady value. When each concentration measured is in error the system oscillalates continuously. These oscillations are shown for measurement errors of 1.5 and 5% in Figures 4 and 5. Since the effect of the measurement error is multiplied in the strength of the oscillation of the measured AIR, measurement errors of 5% and greater are not acceptable. As is discussed later, we have striven to decrease the detector error.

The procedure described above is satisfactory during steady-state operation but care must be taken in getting to the steady state. The simplest method of getting to steady state is to just use the steady-state control. The problem is that response is slow and both concentration and air infiltration rate overshoot their steady value. As Figure 6 shows, it took more than three hours to arrive close to a steady state. This problem can be alleviated by adding an initial injection as shown in Figure 7. However, since the control scheme has no initial information on the air infiltration rate needed by the integral control term, we see an initial dip in the concentration. If we provide an initial guess of the air infiltration rate, the system reaches steady state much more rapidly. As shown in Figure 8, the concentration stays within a few percent of the steady value and the measured AIR value reaches the true value in approximately 1 hour with little overshoot. An additional observation from these simulations is that the concentration approaches the steady value much earlier than the measured AIR reaches the true AIR.

The constant concentration method has been applied for measuring flow rates in a small house treated as a three-zone system. The living room, bathroom and kitchen (combined volume 61 m^3) of this $98 m^3$ house are well connected and are treated as one zone. The two bedrooms (volumes 17 and 20 m^3) are each a zone. Two separate runs were conducted with a two hour gap. The air-infiltration rates calculated for each zone during both runs are shown in Figure 9. Note that there were no sharp discontinuities in the air infiltration rate between the two runs. The concentration was maintained at 200 ppb and 300 ppb during the two runs and remained reasonably steady in each case.

CALIBRATION PROCEDURES

Detector Calibration

Tracer dilution air infiltration measurements depend on the slope of the log-concentration line plotted against time and did not require calibration of the detector for absolute concentration of tracer gas. The development of the constant concentration system has brought about the need for accurate and reliable measurement of the absolute tracer gas concentration. The equation used to calculate the concentration is:

$$C = [K \ln(I_s/I_p)]^{(1/b)} \qquad (18)$$

where C = absolute concentration of sulfur hexafluoride (SF_6)

I_s = standing current

I_p = peak current

K, b are constants

Calibration involves measuring the ratio Is/Ip of a series of known calibration bags and regressing ln(C) vs ln(ln(Is/Ip)) to estimate the constants K and b.

Several steps ensure accurate calibration:

1. a calibration gas of 1% accuracy is carefully diluted to make up the calibration bags;
2. the system is checked for leaks before each calibration;
3. an automated system is used to perform the calibration;
4. the sample flow rate is monitored.

These procedures have yielded precise calibrations over a range of 20-500 ppb (see Figure 10 for a typical calibration curve) with r^2 values consistently over 0.99.

Another factor to consider is whether the detector will perform as well in the field as it does in the laboratory. We have found that the carrier gas flow rate, which depends on delivered pressure and line losses, has a strong effect on the detector calibration -- see Figure 10. Because the flow rate can be changed by over-tightening fittings and sealing leaks, the detector is calibrated in the same state as it is used in the field immediately before it goes into the field. Also, small leaks in the detector's plumbing can cause unknowingly high readings in the field where the background concentration of tracer gas is higher during a measurement run. We have made modifications to the plumbing in the detector to reduce this problem. Presently, injecting 100 cc of pure SF_6 into the detector enclosure (which translates to a concentration of 8,000,000 ppb) does not affect the standing current and is detected as a concentration of less than 5 ppb -- a significant improvement over the unmodified detector.

Injection System

The injection system consists of a series of 10 two-way valves and constant flow restrictors connected to a manifold. The volume of tracer gas released into the building in a cycle is controlled by adjusting the length of time that a valve is open. The calibration consists of finding the relationship between the length of time the valve is open and the volume of tracer released.

Due to regulator "lock up" (the difference in delivered pressure from no flow to full flow), initial pressurization of the line, gas bleeding off after the valve is closed, and other transient effects, the relationship between open time and tracer gas volume is nonlinear for small valve open times (less than 0.5 seconds). After 0.5 seconds the flow rate is constant and the relationship is linear. The calibration is performed for times from the start of the constant flow period to the maximum open time (30 seconds for our constant concentration system). Plotting and regressing volume against time yields an equation of the form Volume = int + (slope) (time). Forcing the curve through the origin (what is done by specifing the nozzle flow by cm^3/sec) results in large relative errors at low open times. Using the calibration shown in Figure 11 as an example, specifying the flow in cm^3/sec overestimates the valve open time by 23% for a volume of 7 cm^3 while the regression gives an open time within 1% of the actual value.

The calibration equipment is simple and precise. The injection line is run into a submerged graduated cylinder and its opening is placed at the same level as the water surface. The volume of gas and the head of water in the cylinder at the end of the valve open time are measured. The volume of gas that would be released at atmospheric pressure is given by:

$$V_{atm} = \frac{P_m \ V_m}{P_{atm}} \tag{19}$$

where

$$P_m = P_{atm} - (\text{inches head}/407.19)$$

CONCLUSIONS

There are a number of techniques suitable for measuring airflows in multizone buildings. Dilution of a single tracer can be used in two zone buildings when the zones are well coupled. Multiple tracer gases are needed to characterize flows among more zones. The number of zones is limited by the number of tracer gases available -- to date as many as four tracer gases have been used simultaneously. Multiple tracer gas experiments are best carried out using a constant injection of tracer gas. The passive constant injection and sampling technique, developed at Brookhaven National Laboratory, is particularly attractive since it can provide data on long-term average airflow rates, potentially at low cost.

The constant concentration method uses a single tracer gas to determine the airflow rates from the outside into each of as many as ten building zones. Although this method does not fully characterize all interzonal airflows in the building, it can be useful in analyzing the energy balance of multizone buildings. Additionally, these measurements can be used to evaluate the dilution of indoor air pollutants and the ventilation efficiency of buildings.

References

Alexander, D.K., Etheridge, D.W., and Gale, R., 1980. "Experimental techniques for ventilation research", in First Air Infiltration Centre Conference: Air Infiltration Instrumentation and Measuring Techniques, Air Infiltration Centre Document AIC-PROC-1-80, pp. 45-71.

Collet, P.F., 1981. "Continuous measurements of air infiltration in occupied dwellings," in Second Air Infiltration Centre Conference: Building Design for Minimum Air Infiltration, Air Infiltration Centre Document AIC-PROC-2-81, pp. 147-160.

Condon, P.E., Grimsrud, D.T., Sherman, M.H., and Kammerud, R.C., 1980. "An automated controlled-flow air infiltration measurement system," in Building Air Change Rate and Infiltration Measurements, (Eds. Hunt, King and Trechsel), ASTM Special Publication 719.

Dietz, R.N., and Cote, E.A., 1982. "Air infiltration measurements in a home using a convenient perfluorocarbon tracer technique," Environment International, Special Issue on Indoor Air Pollution, Vol. 8, No. 1, pp. 419-433.

Dietz, R.N., Goodrich, R.W., and Cote, E.A., 1984 (in Press). "Performance of a passive perfluorocarbon tracer system for building ventilation and air exchange measurement", ASTM Symposium - Measured Air Leakage Performance of Buildings.

Ford, J.K., 1982. "Heat flow and moisture dynamics in a residential attic", Princeton University Center for Energy and Environmental Studies Rept. No. 148.

Freeman, J., Gale, R., and Sandberg, M., 1982. "The efficiency of ventilation in a detached house", Third Air Infiltration Centre Conference: Energy Efficient Domestic Ventilation Systems for Achieving Acceptable Indoor Air Quality, Air Infiltration Centre Document AIC-PRO-3-82, pp. 15.1-15.22.

Grot, R.A., 1980. "A low-cost method for measuring air infiltration rates in a large sample of dwellings", Building Air Change Rate and Infiltration Measurements, (Eds. Hunt, King and Trechsel), ASTM Special Publication 719, pp. 50-59.

Grot, R.A., Hunt, C.M., and Harrje, D.T., 1980. "Automated air infiltration measurements in large Buildings," AIC Conference on Air Infiltration Instrumentation and Measuring Techniques, Air Infiltration Centre Document AIC-PROC-1-80, pp. 103-128.

Harrje, D.T., Hunt, C.M., Treado, S.J., and Malik, N.J., 1975. "Automated instrumentation for building air infiltration measurements," Princeton University Center for Energy and Environmental Studies Rept. No. 13.

Harrje, D.T., Grot, R.A., and Grimsrud, D.T., 1981. "Air infiltration: site measurement techniques", Second Air Infiltration Centre Conference: Building Design for Minimum Air Infiltration, Air Infiltration Centre Document AIC-PROC-2-81, pp. 113-134.

Harrje, D.T., Gadsby, K.J. and Linteris, G.T., 1982. "Sampling for air exchange: rates in a variety of buildings", ASHRAE Transactions, Vol. 88, Part 1.

Hernandez, T.L., and Ring, J.W., 1982. "Indoor radon source fluxes: experimental tests of a two-chamber model", Environment International, Special Issue on Indoor Air Pollution, Vol. 8, pp. 45-57.

I'anson, J.S., Irvin, C., and Howarth, A.T., 1982. "Air flow measurements using three tracer-gases" Building and Environment, Vol. 17, No. 4, pp. 245-252.

Kumar, R., Ireson, A.D., and Orr, H.W., 1979. "An automated air infiltration measuring system using SF_6 tracer gas in constant concentration and decay methods," ASHRAE Transactions, Vol. 85, part 2, pp. 385-395.

Liddament, M. and Thompson, C., 1983. "Techniques and instrumentation for the measurement of air infiltration in buildings - A brief review and annotated bibliography," Air Infiltration Centre Document AIC-TN-10-83.

Lundin, L., and Blomsterberg, A., 1983. "An automated air infiltration measurement system - Its design and capabilities, preliminary experimental results", Air Infiltration Rev. Vol. 4, No.1.

Perera, M.D.A.E.S., Walker, R.R., and Oglesby, O.D., 1983. "Ventilation rates and intercell airflow rates in a naturally ventilated office building", Fourth Air Infiltration Centre Conference: Air Infiltration Reduction in Existing Buildings, Air Infiltration Centre Document AIC-PROC-11-83.

Sandberg, M., 1981. "What is ventilation efficiency?", Building and Environment, Vol 16, No 2, pp. 123-135.

Sinden, F.W., 1978. Multi-chamber theory of air infiltration", Building and Environment, Vol. 13, pp. 21-28.

ACKNOWLEDGMENTS

The authors wish to thank Peter Collett, Technological Institute, Denmark, for supplying us with a developed computer program and for demonstrating the capabilities of his system, which convinced us of the merits of the constant concentration approach. We also wish to thank our former students, Tim McNally who worked with Dr. Collett in Denmark, and Kevin Gift who helped to adapt the Danish program to our system.

We also acknowledge the support of the United States Department of Energy who supported this effort under contract no. DE-AC02-77CS20062.

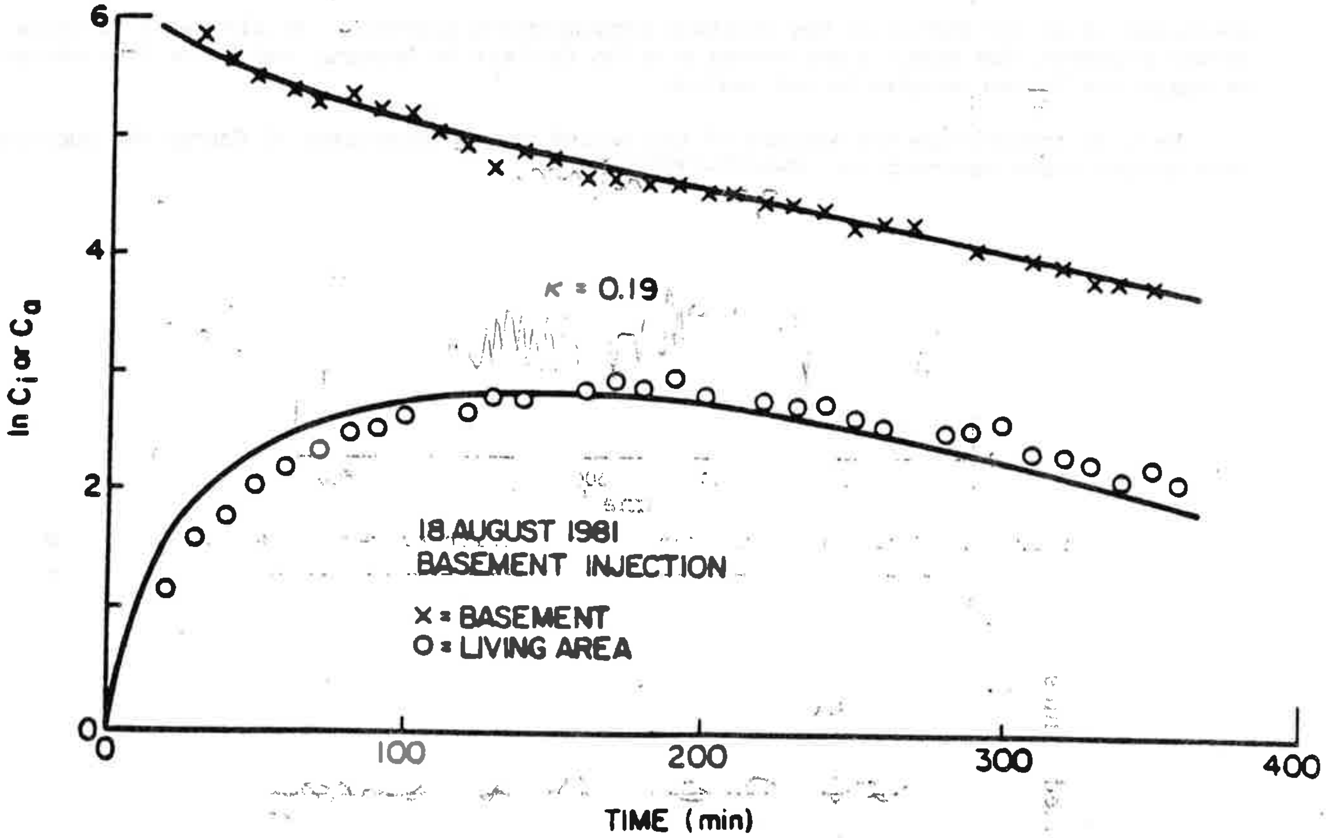

Figure 1. Single tracer, two-chamber measurements

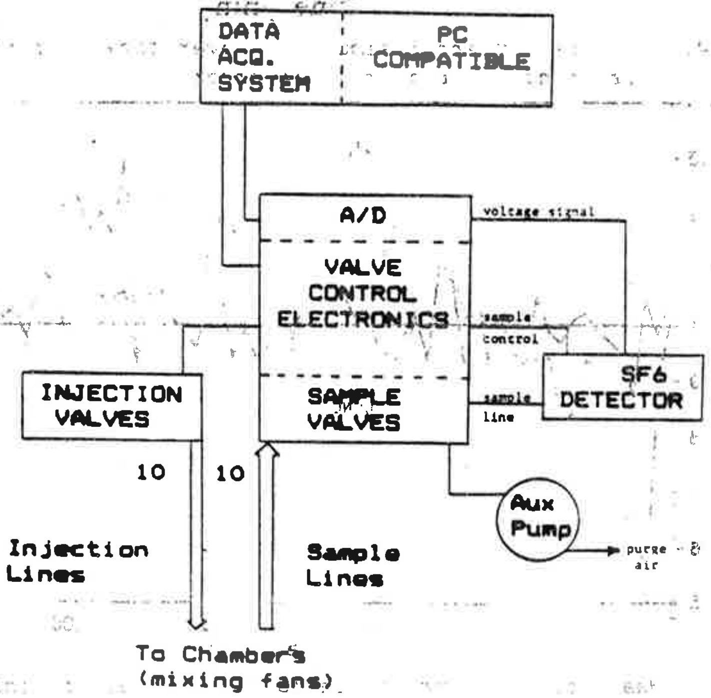

Figure 2. Block diagram of constant concentration system

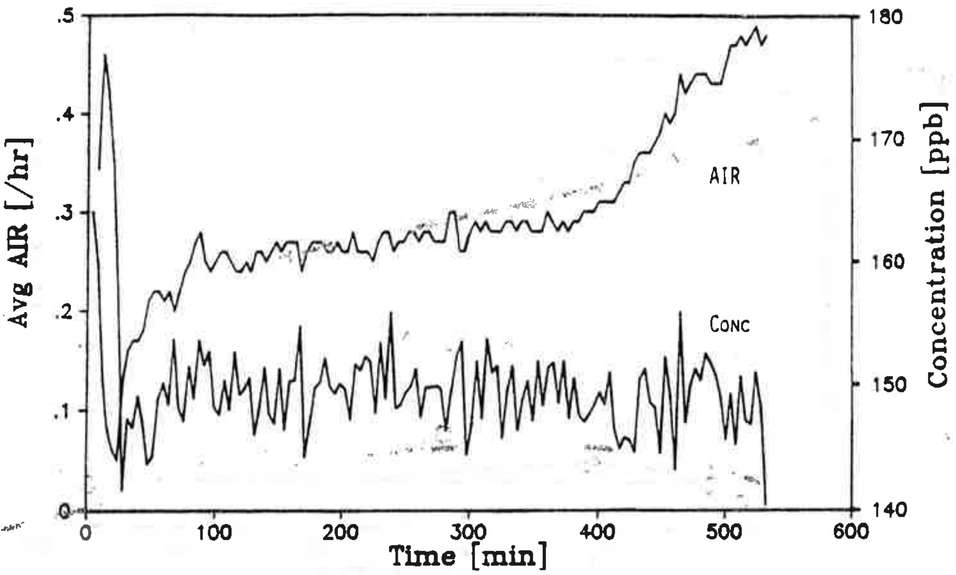

Figure 3. Single zone constant concentration tracer gas measurements

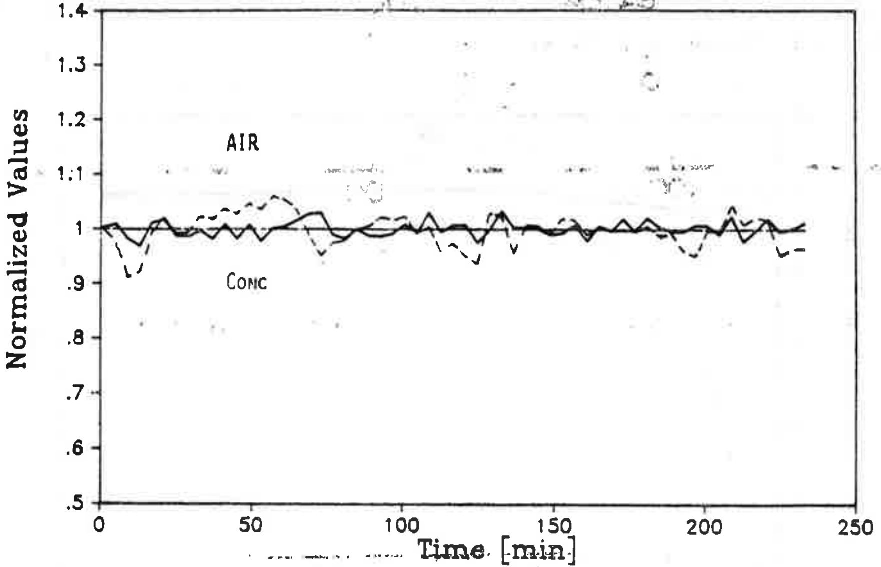

Figure 4. Measurement error simulation over time; air infiltration = 0.3 air changes per hour, 1.5% error

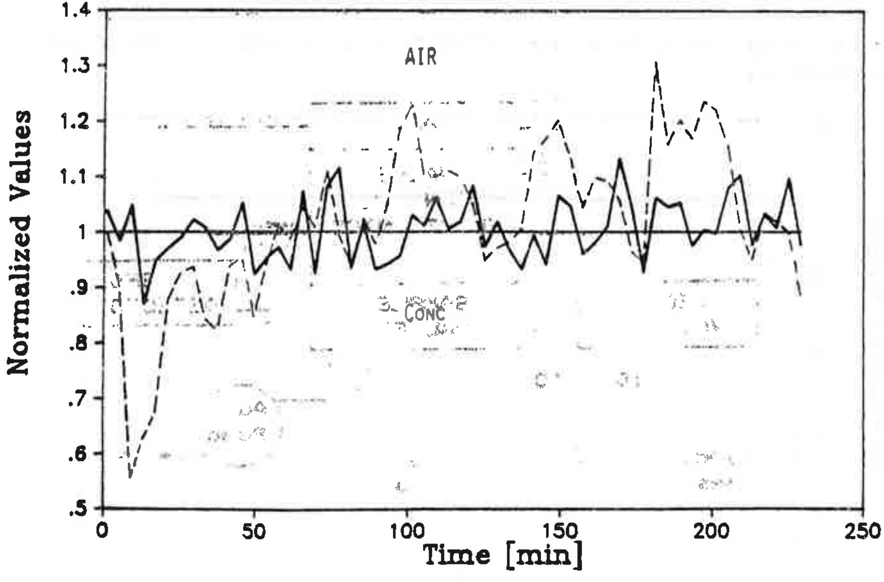

Figure 5. Measurement error simulation over time, air infiltration = 0.3 air changes per hour, 5% error

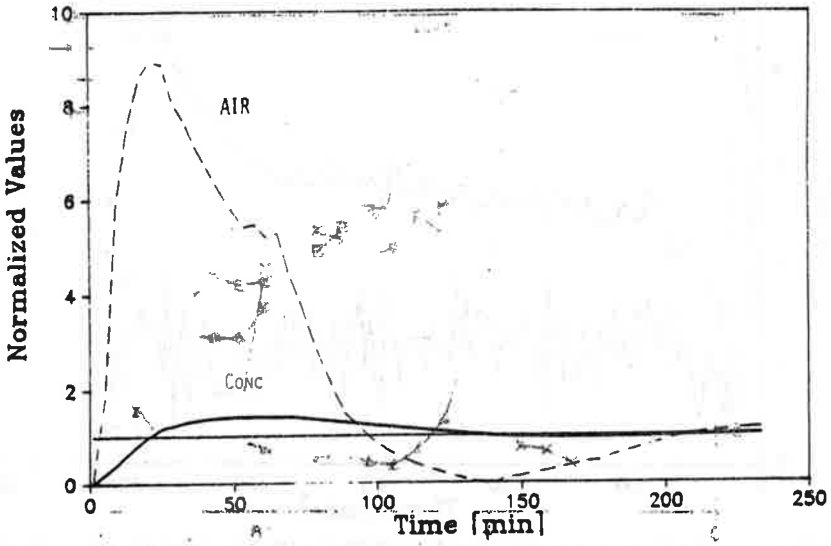

Figure 6. Initial response simulation; no initial tracer gas injection, air infiltration = 0.3 air changes per hour

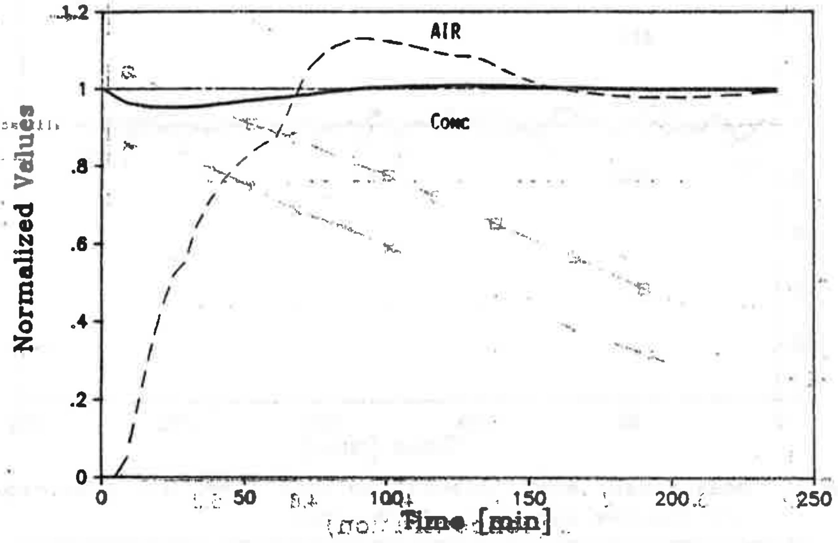

Figure 7. Initial response simulation; initial tracer gas injection but not initial air infiltration

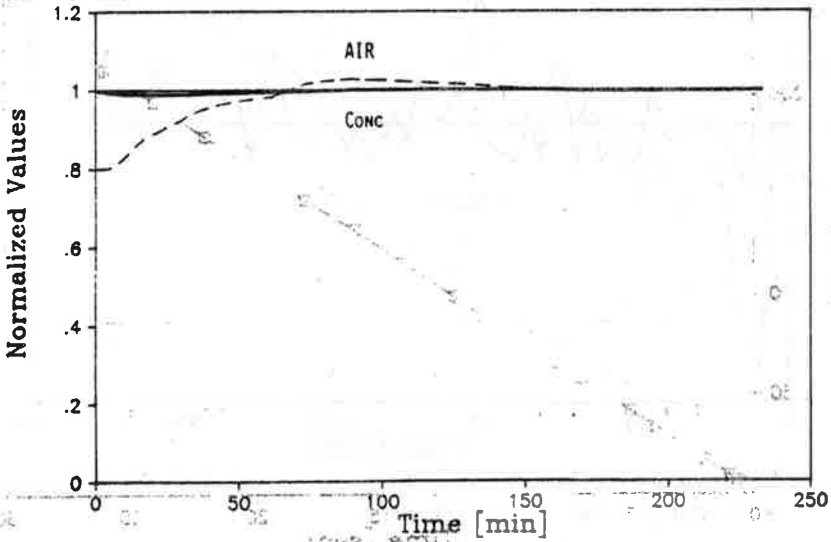

Figure 8. Initial response simulation; initial tracer gas injection, initial air infiltration guess 80% of true rate

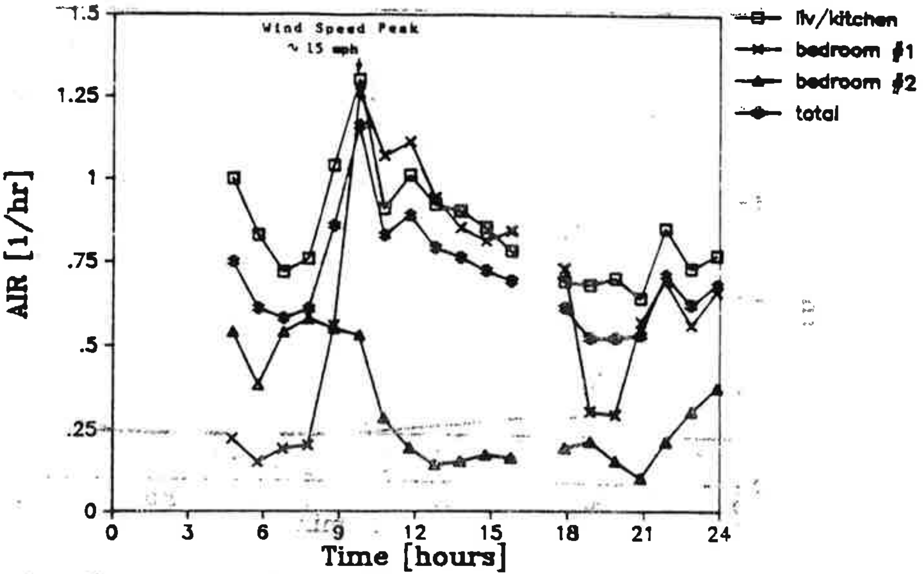

Figure 9. Hourly air infiltration rates in three zones of a small house

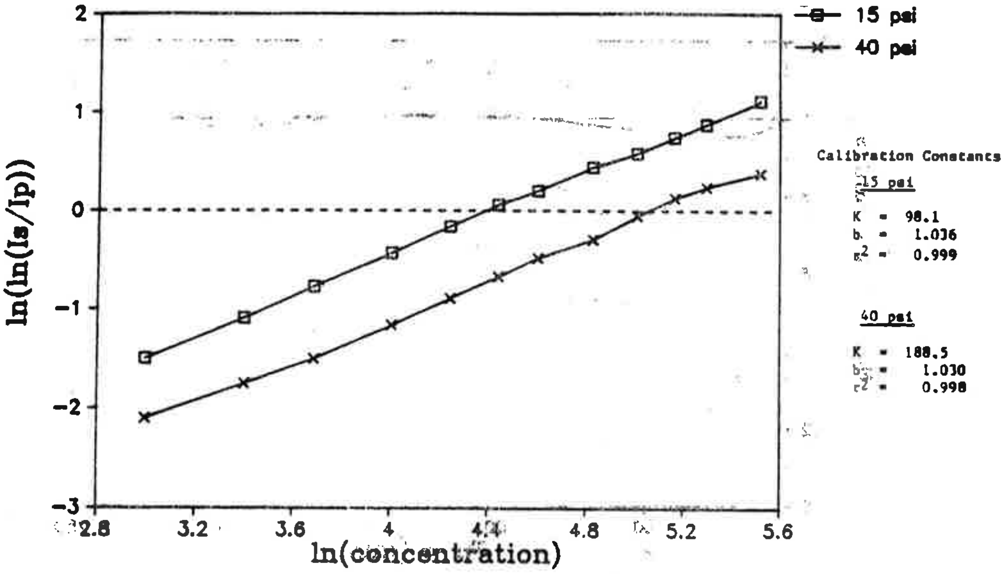

Figure 10. Detector calibration for variable carrier gas pressure

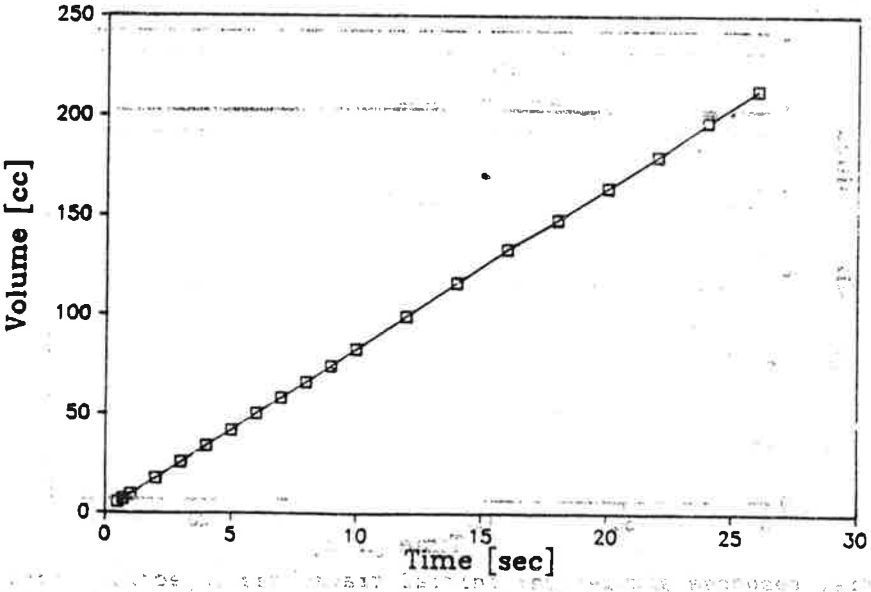

Figure 11. Tracer gas injection orifice calibration, 0.5 to 30 seconds

[illegible]

[illegible]

[illegible]