AIC (476)

991

No. 2657

AN APPRAISAL OF THE SULPHUR HEXAFLUORIDE DECAY TECHNIQUE FOR MEASURING AIR INFILTRATION RATES IN BUILDINGS

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INTRODUCTION

Sulfur hexafluoride is useful as a tracer gas for air-infiltration studies because sensitive detectors measuring in the parts per billion range are readily available. In addition, the gas is non-toxic and can readily be separated from other detectable gases chromatographically.

Sulfur hexafluoride is, however, a heavy gas and potentially difficult to mix with air. This study compares the air change rates measured with SF_6 and CO_2 using the tracer gas decay technique and the fan extraction method over a wide variety of test chamber sizes and mixing systems. Three important aims are:

1) To provide direct experimental evidence that conventional air handling systems or an arrangement of floor fans comes close enough to achieving the perfect mixing required in principle.

2) To establish limits of accuracy and reproducibility for SF_6 decay results.

3) To refine our SF_6 tracer decay experimental procedure for further infiltration studies.

THE TRACER GAS DECAY METHOD

This method has been used and documented extensively. Briefly, the tracer gas concentration is increased in the test space, to the top end of the gas analyzer measuring range. The air in the test space is continuously mixed to a uniform composition, and the tracer gas concentration is monitored as it decreases with time. The infiltration rate is calculated on the basis of a uniform gas mixture and a steady leakage rate from the expression

$$C_T = C_o e^{-nT}$$

and hence

$$n = \frac{1}{T} \ln \frac{C_o}{C_T}$$

where

C_T = tracer gas concentration at time T
C_o = tracer gas concentration at time T = 0
n = air changes per unit of time

The requirement of uniform mixing is almost never rigorously satisfied so it must be shown either analytically or experimentally that mixing provisions are adequate. The latter method of validation has been chosen here because detailed air flow patterns in buildings are not amenable

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to calculation procedures. A number of simple models of incomplete mixing have been outlined by Hunt and Burch [1] representing the extreme cases of "perfect nonmixing" and a "dead spot". These maladies show up as a nonlinear log linear plot of concentration vs. time, sounding a warning that errors due to mixing are present. The converse of this argument is not true, however, as a straight line log linear plot cannot be used as complete evidence of perfect mixing [2].

Samples were collected from the main stream of air movement, e.g., a return air duct, when an air handling system was in operation. When floor fans were used sample collection tubes from a number of rooms were manifolded together.

A detailed flow diagram of the tracer gas detection equipment is given in Fig. 1. This includes all the connections and flow rates used to make simultaneous measurements of CO_2 and SF_6 concentrations. The two most important maintenance areas were

a) The detectors must be kept free of solid material. To this end the electron capture device was occasionally flushed with ethyl alcohol.

b) The chromatograph column needed occasional cleaning with pure argon at 100°C.

The SF_6 detector used in this series of tests was a chromatograph equipped with an aluminum oxide column and a pulsed mode electron capture detector containing a Ni^{63} radioactive source. Oxygen, which is also an electron capturing gas, elutes first from the room temperature column and is followed by SF_6, which is measured separately. The detector is also sensitive to a number of other materials notably fluorocarbons in air-conditioning systems and aerosol propellants. Freon tends to move through the column very slowly, causing the background standing current of the detector to drift.

FORCED AIR EXCHANGE RATES

As an independant check of air change rates measured with the two tracer gases, the air discharge rate from the test space was directly controlled and metered. Air was exhausted from the test space using suitable lengths of duct and a fan, Fig. 2. The flow rate was measured on the discharge side of the fan and held steady at a sufficiently high level to maintain positive pressure differentials across all external walls. Pressure taps were mounted at midheight on the external walls and referenced indoors across a pressure transducer. Strip chart records of pressure differentials were retained as evidence that all leakage paths were being driven in the same direction, outside to inside, and that all mass transfer inside to outside was accounted for downstream of the fan. A laminar flow element (MERIAM LFE ELEMENT) accurate to 3% of the measured flow rate was used in house and room tests. For high flow rate measurements in schools, air velocity pressure averaging tubes with 5% accuracy were used. Laminar flow elements and pressure averaging tubes were calibrated in the laboratory by Pitot traverse.

COMPARISON OF TRACER GAS DECAY AND FAN INDUCED AIR CHANGE RESULTS

The comparison of air change rates measured with SF_6 and CO_2 tracer gas techniques and the fan extraction method ranged over a wide variety of test chamber sizes and mixing systems. Early calibration and testing of the SF_6 electron capture device began with a sealed metal drum in the laboratory. Later the equipment was moved into the field where a number of single rooms, a two-storey detached house with basement, and a large open plan school were used as test chambers. The results for each are discussed separately.

Rooms

Room A is located on the top floor of a two-storey house and has two external walls and a ceiling adjacent to the roof space. Pressure taps were attached across each external wall, the ceiling, and internal partitions. Two floor fans each with flow rates of 1000 L/s were used to mix the air continuously during testing and fan-extracted air was drawn from a point 1 m inside the room (Fig. 3). All obvious leaks in the room were sealed with tape.

Tracer gas results plotted against fan-induced air change rates in Fig. 4 demonstrate good agreement between measurements. Best fit linear equations of the type

$$(\text{tracer gas air change rate}) = K\ (\text{fan induced air change rate})$$

were chosen and the calculated values of K are as follows:

$$K_{SF_6} = 0.97 \pm 0.09$$
$$K_{CO_2} = 0.99 \pm 0.08$$

The line of agreement K = 1 falls within the 95% confidence limit, indicating that the data do not support a systematic difference between the tracer gas decay and fan extraction methods. The 95% confidence limit to K is based on the scatter of data around the best fit line rather than on experimental errors given in Appendix I for ideal laboratory measurements. These experimental errors fall short of explaining the scatter in Fig. 4, indicating that a small increase in experimental error may be necessary to account for incomplete mixing.

Air change rates measured in room A were higher than natural infiltration rates expected in tight buildings. To explore this lower range, and retain fan extraction control over the infiltration rate, it was necessary to find a room shielded from the normal driving forces of infiltration. This requirement was satisfied by room B, located in the core of a large open plan school with walls and ceiling shielded from direct wind action and very small inside to outside temperature differences. The school air handling system was turned off and air within the room space stirred by two floor fans. A single pressure tap monitored during tests gave evidence of a positive pressure difference down to an induced air change rate of 0.1 AC/h. Below this the pressure difference was too small to measure.

Agreement between the two tracer gas methods (Fig. 5) was maintained to the lowest air change rates but with considerable departure from the fan-induced air change rate. This difference was not found in the laboratory using a sealed metal drum (Fig. 6), indicating that either absorption of tracer gases or an additional driving force of infiltration was present inside the room.

Absorption should not depend on the fan-induced air change rate and is unlikely to proceed at the same rate for both tracer gases. It is suggested that the high internal mixing rate of 2000 L/s (equivalent to turning over the air 326 times per hour) in Room B caused drafts large enough to establish localized pressure differences across the walls and induced an air leakage rate of approximately 0.13 AC/h. As the fan-induced pressure difference is increased, the air mixing-induced pressure differences are exceeded until at about 0.4 AC/h all the leakage from the room is accounted for by the fan extraction rate. Measurements of fan-induced air velocities close to the walls of a similar sized room in the laboratory have suggested that the observed leakage rate with zero fan extraction is not unexpected. This observation illustrates that the choice of mixing rate is a compromise between a high air circulation rate to give the perfect instantaneous mixing required in principle and a low but adequate air circulation rate to minimize the mixing-induced air leakage, particularly at low air infiltration rates.

Nonzero infiltration rates have been noted before in calm temperate conditions. Hunt and Burch [1] suggested that small thermal gradients were the cause, and Blomsterberg and Harrje[3] noted a similar result in the Twin Rivers town houses. The thermal gradient hypothesis does not apply in this case because a large temperature difference would be required to induce 0.13 AC/h.

In Fig. 7 the two tracer gas methods are compared with the following best linear relationship:

$$(SF_6 \text{ air change rate}) = 1.16\ (CO_2 \text{ air change rate}) - 0.05$$

The units are air changes per hour and the random error for a single measurement is approximately ±0.08 at the 95% confidence level.

<u>Houses</u>

House C is a two-storey dwelling with basement, located in a suburban section of Ottawa, Canada. Fig. 3 shows the position of pressure taps and extraction fan. The forced air distribution system provided mixing for all results listed under House C. House D is the same building with all duct registers sealed and a series of eight 1000 L/s floor fans arranged to promote mixing between rooms and levels as well as within rooms.

Figs. 8 and 9 compare the tracer gas results with fan-induced air change rates. Best fit linear equation of the type

$$(\text{tracer gas air change rate}) = K\ (\text{fan induced air change rate})$$

yield the following values of K.

Mixing arrangement	Tracer gas	K±95% Confidence limits
furnace fan, 4.7 AC/h*	CO_2	0.94 ± 0.08
"	SF_6	1.01 ± 0.08
floor fans, 74.6 AC/h	CO_2	0.99 ± 0.06
"	SF_6	1.06 ± 0.10

showing that there is no systematic difference between tracer gas and fan-induced air change rates. The random difference between simultaneous tracer gas and fan-induced results is about 0.06 AC/h at the 95% confidence level.

A comparison of the two tracer gas techniques is worthy of some attention since Fig. 10 shows a systematic difference at high and low air change rates with improved agreement at a crossover region around 0.5 AC/h. A number of additional data points in the low air change range were measured during a study of natural infiltration. They are insufficient in number to stand alone but make a useful addition to the data obtained under fan control. The best linear fit takes the form:

$$(SF_6 \text{ tracer gas result}) = 1.16\ (CO_2 \text{ tracer gas result}) - 0.07$$

The difference between this best fit to the data and the line of agreement is significant at the 95% level. The trend is the same for both mixing strategies and the question of which tracer gas is the more accurate cannot be resolved by comparison with fan extraction results because the differences are lost in experimental error. Grimsrud et al [4] reported SF_6 decay results that exceeded comparitive measurements with lighter tracer gases by a similar margin. These results lie in the range of 0.5 to 1.6 AC/h with no comparable data available for low air change rates where our results show the opposite trend. The differences as shown in Fig. 10 are only just visible above experimental error, and the cause of this difference has not been isolated. It appears to be independant of the test volume and method of mixing and has some support from independent studies [4]. It has been generally assumed that mixing within the room and leakage from the room by molecular diffusion are very small effects compared with the convective and velocity driven components, but with the large difference in molecular weight between SF_6 and CO_2, the effect of molecular diffusion may not be entirely discounted.

School

The school chosen for a comparison of SF_6 decay results with fan extraction rates was a large open plan building on an exposed site. Fig. 3 shows the location of pressure taps and three identical fan extraction units. Individual flow rates were measured at 10 diam downstream from the fan with a pair of velocity pressure averaging tubes which were carefully calibrated in the laboratory by Pitot traverse. Previous tests with one large extraction fan were found to cause a significant imbalance in the tracer concentration.

The best linear relation between the data in Fig. 11 and the origin is

$$(SF_6 \text{ air change rate (AC/h)}) = 1.07\ (\text{fan extraction rate (AC/h)}).$$

This result might indicate that the effective volume occupied by the tracer gas falls about 7% short of the total building volume, giving a rough measure of the amount of dead air space and furniture, etc. The data do not, however, allow this volume to be calculated with a reasonable degree of confidence. In statistical terms, the line of agreement falls within the 95% confidence limits imposed on K by random fluctuations in the data. Once again these random variations are larger than found in Appendix I for an ideal well mixed test space.

CONCLUSIONS

The main object of this work was to confirm experimentally that conventional air handling systems or portable floor fans can provide adequate mixing for tracer gas decay measurements of infiltration. In addition to showing that these provisions are satisfactory, the results warn that the mixing operation may become the dominant driving force of infiltration during calm and temperate climatic conditions.

Laboratory checks of calibration and reproducibility led the authors to expect SF_6 tracer gas air change results with ±0.02 AC/h accuracy. In the field, the agreement with independent measurements suggest that ±0.08 AC/h is a more reasonable measure of experimental error at the 95%

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* Fan mixing rate

confidence level.

There is a small systematic difference between the behavior of CO_2 and SF_6 that leads to relatively high SF_6 results above 0.5 AC/h and relatively low results below.

APPENDIX I

EXPERIMENTAL ERRORS

Air change rates measured with the tracer gas decay technique have a margin of error derived from several sources. The systematic error caused by incomplete mixing is perhaps the most interesting and least understood, and these experiments were designed to confirm that mixing using standard air handling systems was adequate. The remaining instrument errors amount to ± (0.02 + 2%) for SF_6 results and ± (0.01 + 3%) for CO_2. They were assessed in the laboratory under conditions of ideal mixing and are made up of the following components.

1) Baseline error (uncertainty in the background tracer gas concentration).

2) Random error in the detector output.

3) Uncertainty in the functional shape of detector output vs. tracer gas concentration.

All are relevant to CO_2 measurements but only the last two need to be considered for SF_6 since baseline error can be treated as a random instrument error.

BASELINE ERROR

The effect of an error in the background level of CO_2 can be estimated as follows:

$$n \pm \Delta n = \frac{1}{T} \ell n \frac{C_o \pm \Delta C}{C_T \pm \Delta C}$$

ΔC = uncertainty in background concentration

Δn = corresponding uncertainty in air change rate

$$2\Delta n = \frac{1}{T} (\ell n \frac{C_o C_T + (C_o - C_T)\,\Delta C}{C_o C_T + (C_T - C_o)\,\Delta C})$$

$$\approx \frac{1}{T} (\ell n\ C_o C_T\ (1 + X) - \ln\ C_o C_T\ (1 - X))$$

$$X = \frac{(C_o - C_T)\,\Delta C}{C_o C_T}$$

$$\approx \frac{1}{T} (X - \frac{1}{2} X^2 - (-X - \frac{1}{2} X^2\ ))$$

$$-1 < X < 1$$

$$\Delta n \approx \frac{1}{T} \frac{(C_o - C_T)\,\Delta C}{C_o C_T}$$

Typical values of C_o, C_T and $\Delta C = 0.01\ C_o$ yield an uncertainty in n of approximately 2%.

RANDOM ERROR

There is a random error in each SF_6 concentration measurement made up of chart reading inaccura[illegible] and instrument fluctuations. The size of this random error has been determined while sampling constant composition test gases and found to be typical of the scatter of points around the regression line for concentration decay in an ideal test chamber in the laboratory. If the res[illegible] duals are assumed to be normally distributed, then the variance in the calculated air change ra[illegible] can be written as:

$$\sigma_n^{\ 2} = \sigma^2 \ / \sum_{i=1}^{m} \ (T_i - \bar{T})^2$$

where

T_i = sample time; $\bar{T}$ = mean of sample times
m = number of concentration data points

and

$$\sigma^2 \simeq \sum_{i=1}^{m} (\ln C_i - \ln \hat{C}_i)^2/(m-2)$$

where

C_i = the experimental SF_6 concentration at T_i
$\hat{C}_i$ = the regression estimate of C_i at T_i.

The value of σ^2 averaged over 20 half hour long tests translates to approximately 0.3% of the SF_6 concentration. For a sampling frequency of once each 5 min., the 95% confidence limits for a test lasting 30 min. is 0.04 AC/h and for an hour long test 0.02 AC/h. Additional error values can be deduced from the rule: halving the test duration doubles the margin of error.

Carbon dioxide concentrations were recorded continuously, but only data points at 5 min. intervals were collected and used in a log-linear regression. The random error was about half of that for SF_6 value.

DETECTOR CALIBRATION

Two different methods were used to calibrate the most sensitive range of the SF_6 detector. The first employed an air tight metal drum as the test space with an internally mounted fan to provide mixing. The tracer gas concentration was increased step by step using a gas syringe and concentration vs. response is shown in Fig. A1. Sensitivity does decline with concentration and the expression $C = 0.1712\ D^{1.022}$ is the best fit to data

where

C = concentration, ppb
D = detector, millivolts.

The consequence of assuming a linear sensitivity can be estimated as

$$n = \frac{1}{T} \ln \frac{D_o}{D_T}$$

$$\Delta n = \frac{1}{T} \left(\ln \frac{D_o}{D_T} - \ln \frac{0.1712\ D_o^{1.022}}{0.1712\ D_T^{1.022}}\right)$$

$$= (1 - 1.022) \frac{1}{T} \ln \frac{D_o}{D_T}$$

$$\Delta n = 0.022\ n$$

which leads to a 2% underestimate of n.

The additional points on Fig. A1 were obtained using the house as a test chamber and accounting for infiltration using a simultaneous CO_2 decay test.

The CO_2 detector has been periodically calibrated using certified mixtures of CO_2 and N_2. The calibration curve in Fig. A2 is linear within experimental error.

REFERENCES

1. Hunt, C.M. and Burch, D.M., Air Infiltration Measurements in a Four-Bedroom Townhouse Using Sulphur Hexafluoride as a Tracer Gas. ASHRAE Trans, Vol. 81, Pt. 1, pp. 186-201, 1975.

2. Shaw, C.Y. and Tamura, G.T., Mark XI Energy Research Project Air Tightness and Air-Infiltration Measurements. National Research Council of Canada, Division of Building Research, Building Research Note 162, June 1980.

3. Blomsterberg, A.K., and Harrje, D.T., Evaluating Air Infiltration Energy Losses, ASHRAE Journal, pp. 25-32, May 1979.

4. Grimsrud, D.T., Pearman, A.N., Sherman, M.H., Harrje, D.T., and Janssen, J.E., An Intercomparison of Tracer Gases Used for Air Infiltration Measurements, ASHRAE Trans, Vol. 86, Pt. 1, 1980.

ACKNOWLEDGMENTS

This work was undertaken in Ottawa by the Division of Building Research, National Research Council of Canada. The senior author is a guest worker from the Building Research Association of New Zealand. The authors wish to acknowledge the cooperative effort of both organizations in supporting this project. In addition, they wish to thank the Carleton Board of Education and W.C. Brown, project manager of the Mark XI Energy Research Project (a joint HUDAC/NRC study), for their cooperation and assistance in conducting the experiments.

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

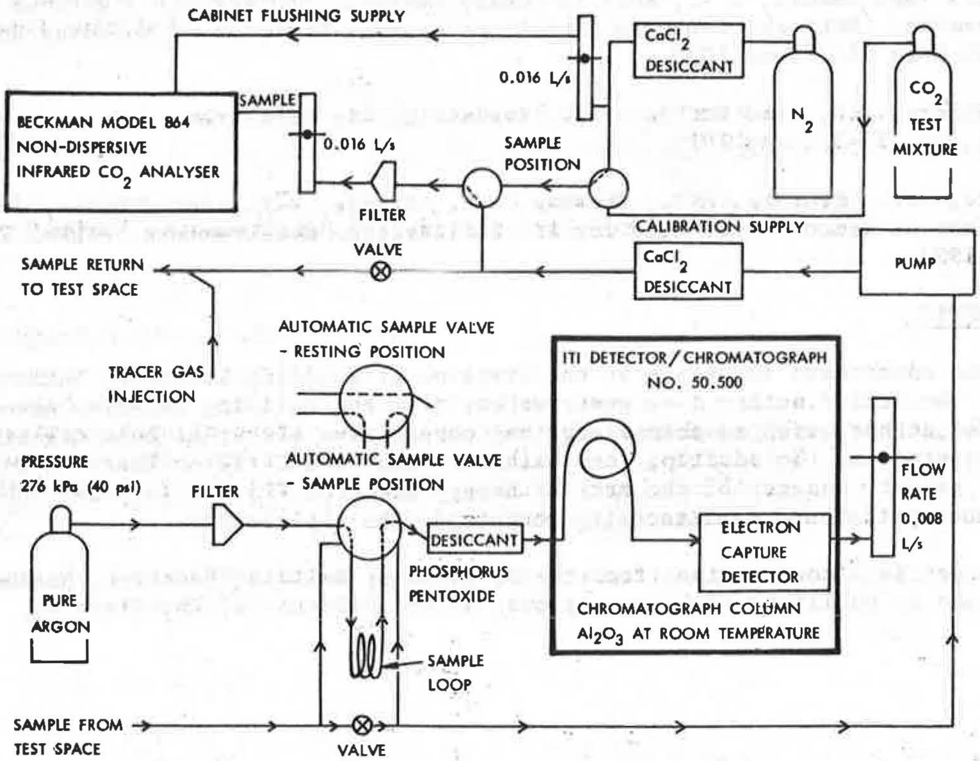


Fig. 1 Tracer gas detection equipment

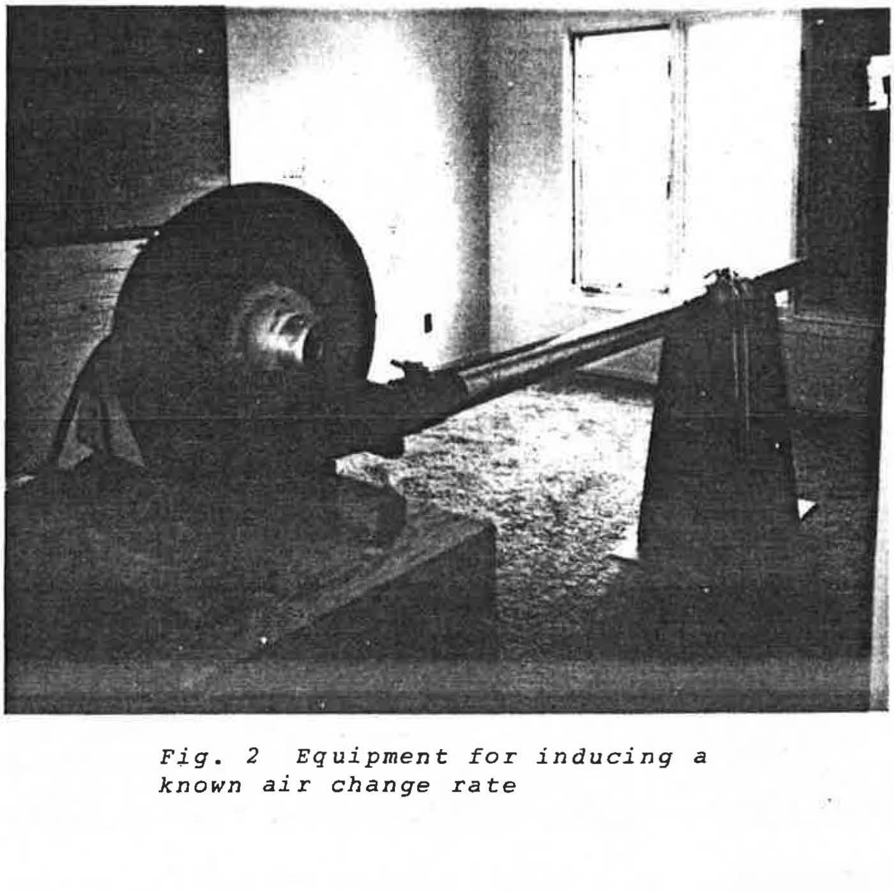
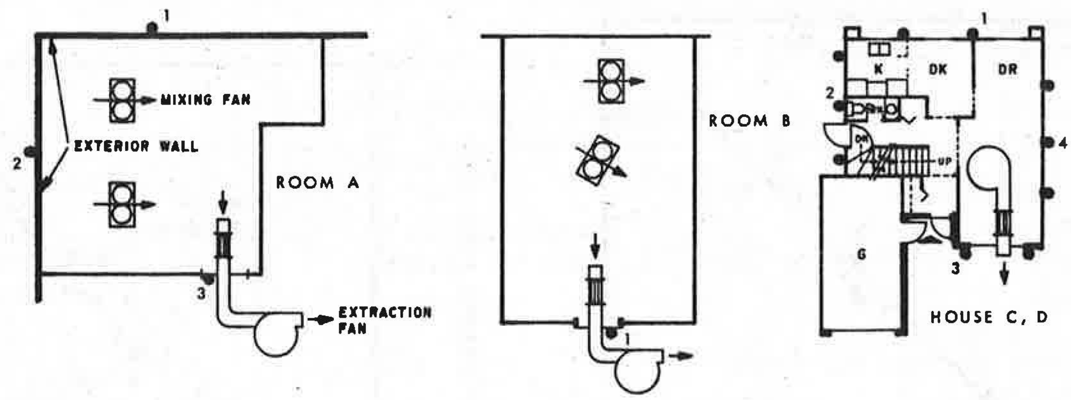
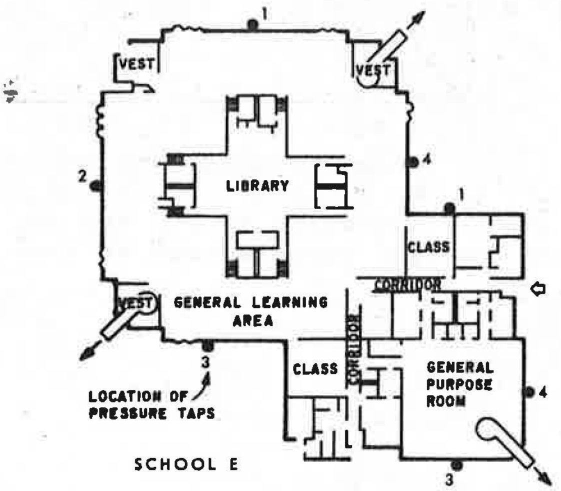


Fig. 2 Equipment for inducing a known air change rate





SPACE	DIMENSIONS OF TEST SPACES				
	ROOM A	ROOM B	HOUSE C	HOUSE D	SCHOOL E
FLOOR AREA, m^2	8.60	9.1	118	118	3003
VOLUME (INCLUDING BASEMENT), m^3	19.50	22.1	386	386	11900
AIR FLOW RATE FOR MIXING FANS, L/s (ac/h)	2000 (369)	2000 (326)	500 (4.7)	8000 (74.6)	12000 (3.6)
NATURE OF INTERNAL PARTITIONS	NIL	NIL	2 STOREY, 3 BEDROOM WITH BASEMENT		OPEN PLAN

Fig. 3 Details of test locations

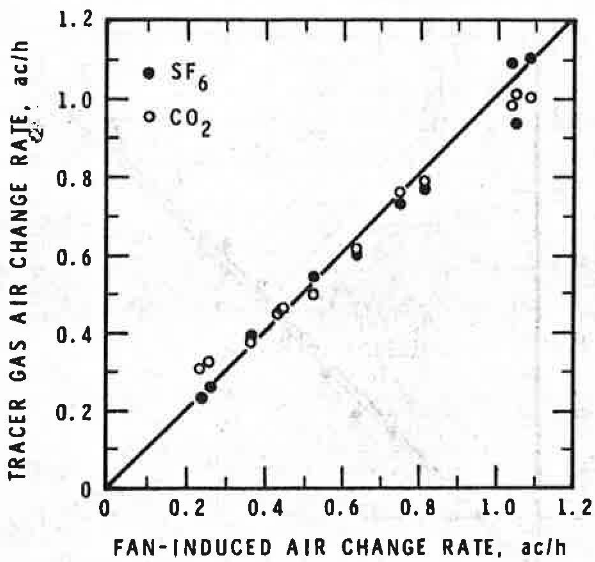


Fig. 4 Comparison of tracer gas and fan-induced air change rates in Room A

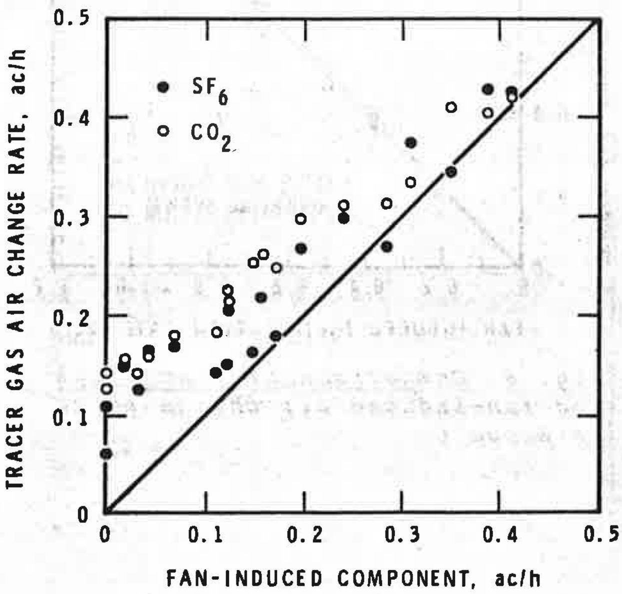


Fig. 5 Effect of fan-induced leakage on tracer gas air change rate in Room B

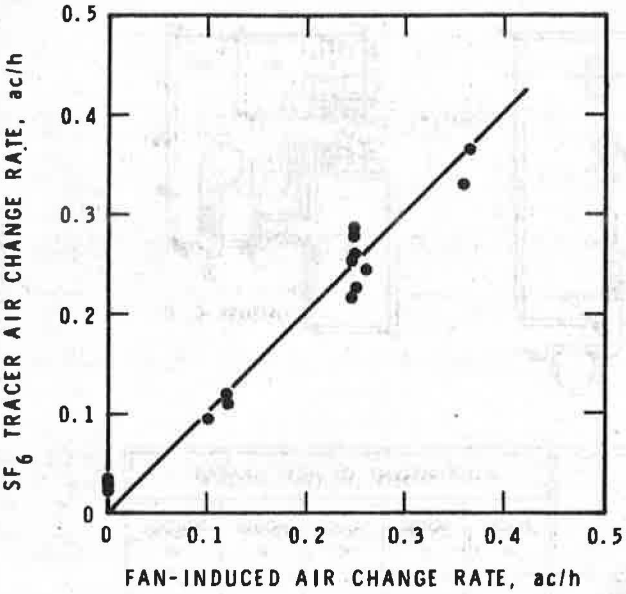


Fig. 6 Comparison of SF_6 tracer gas and fan-induced air change rates in a metal drum

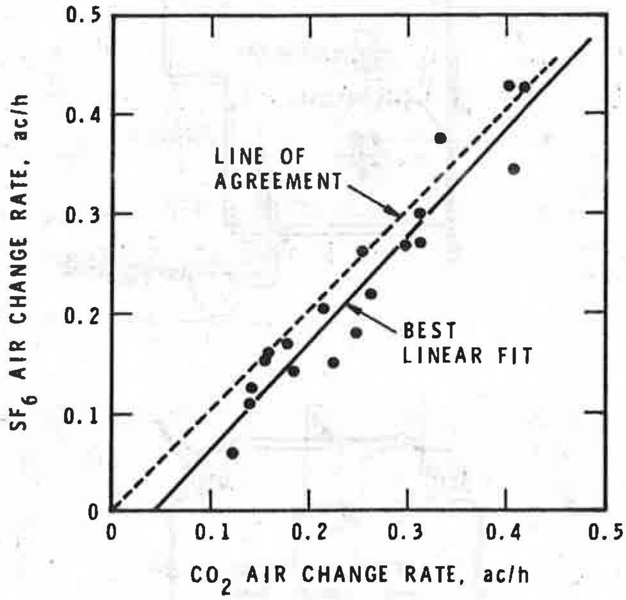


Fig. 7 Relation of SF_6 and CO_2 tracer gas measurements in Room B

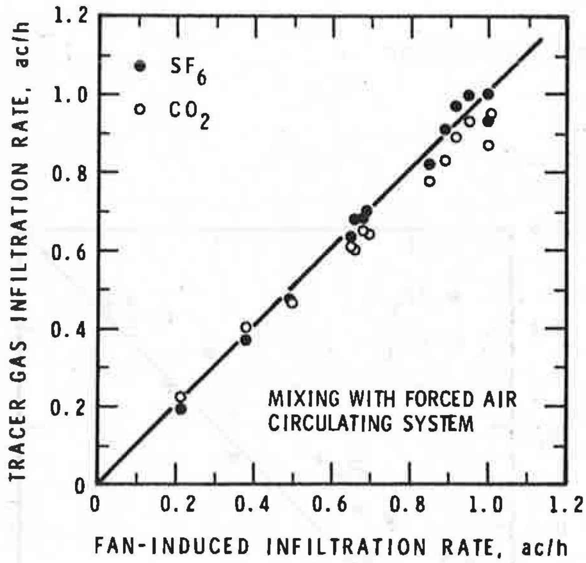


Fig. 8 Comparison of tracer gas and fan-induced air change rates in House C

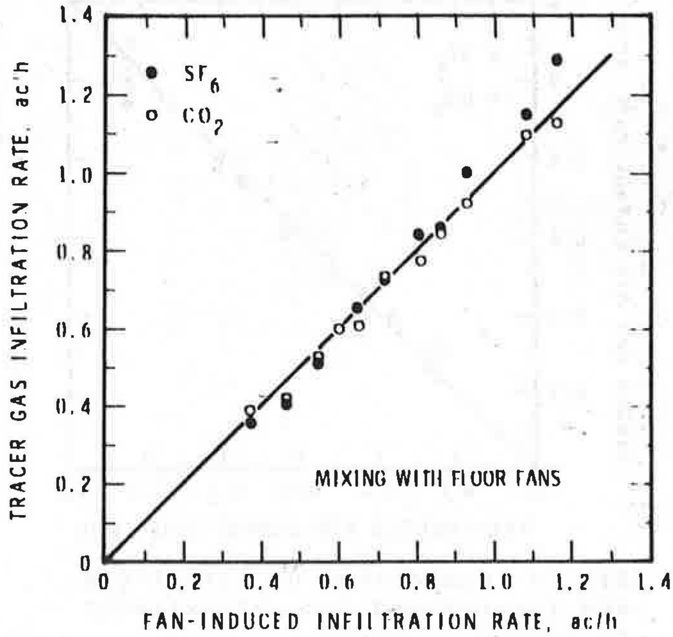


Fig. 9 Comparison of tracer gas and fan-induced air change rates in House D

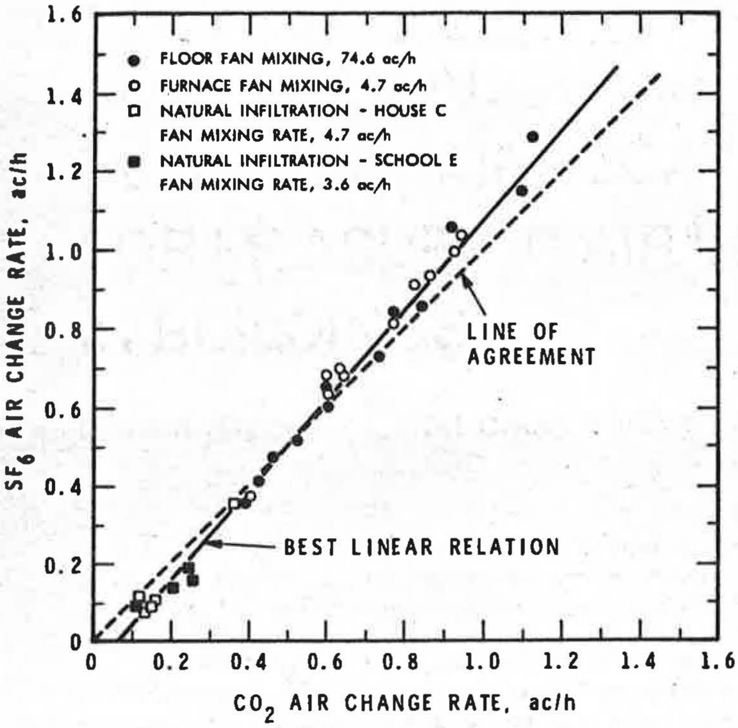


Fig. 10 Relation of simultaneously measured CO_2 and SF_6 tracer gas decay rates

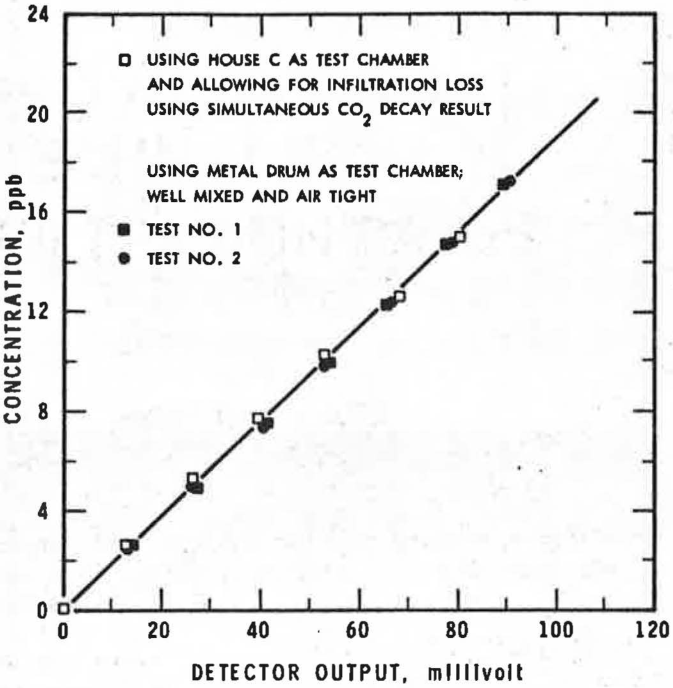


Fig. A1 SF_6 detector calibration

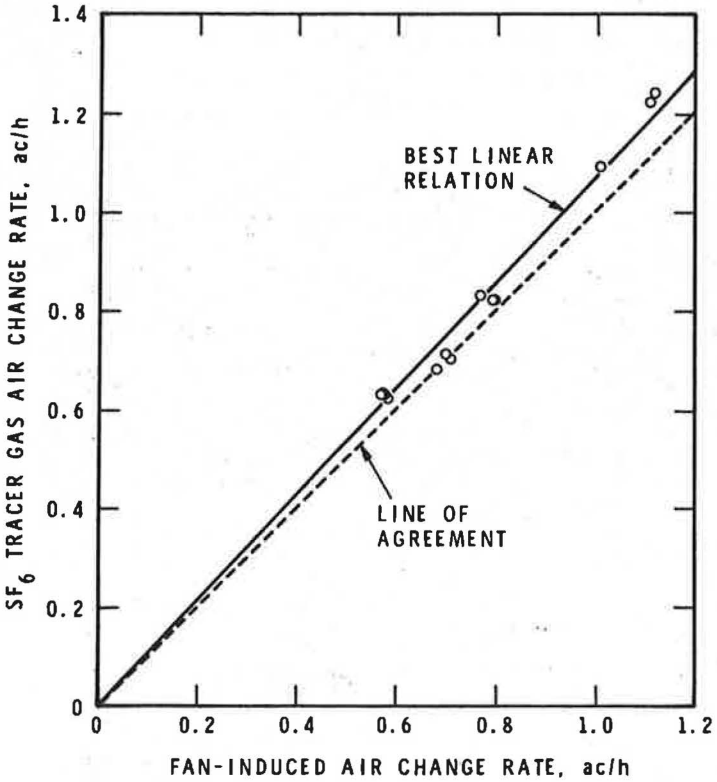


Fig. 11 Comparison of SF_6 tracer gas and fan-induced air change rates in School E

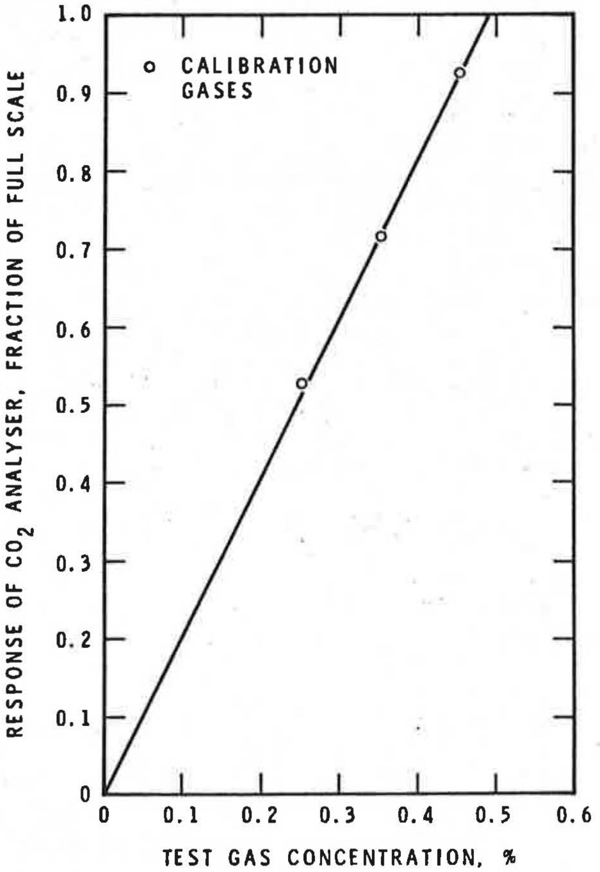


Fig. A2 Calibration of CO_2 analyzer