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AIR INFILTRATION AND BUILDING FACTORS: COMPARISON OF MEASUREMENT METHODS

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INTRODUCTION

The air exchange rate for a building is the rate at which indoor air is exchanged with outdoor air due to the continual transfer of air across the building envelope. The rate of air exchange affects indoor air quality. Depending on the specific situation, air exchange can comprise as many as three components: infiltration, natural ventilation, and mechanical ventilation. A pressure difference between the indoors and outdoors caused by indoor-outdoor temperature differences or by wind is responsible for infiltration of air into a structure with closed windows and doors. Natural ventilation occurs when air flows into and out of a structure through open windows and doors. Mechanical ventilation refers to air exchange that is driven by a motorized system or fan. Local or spot ventilation relates to only a part of a building, as is the case with a bathroom exhaust fan.

There are at least two fundamental approaches to measuring air exchange: (1) pressurization techniques, which use measured pressure-flow relationships to evaluate building tightness, and (2) tracer-gas techniques, which use measured concentrations of specially released tracers to evaluate air exchange. As part of an indoor air quality survey that GEOMET Technologies, Inc., conducted in Texas during the 1984-1985 heating season, air exchange was measured in residences using a pressurization technique and two different tracer-gas techniques. Selected questions were posed to occupants to quantify building factors and ventilation practices. In this paper, the measurement methods are described and empirical relationships derived from measurement results are presented.

EXISTING METHODS FOR MEASURING AIR EXCHANGE[1]

Under normal conditions, the air exchange process is driven by indoor-outdoor pressure differences that amount to a few pascals (Pa). Pressurization techniques artificially increase this pressure difference to evaluate the leakage characteristics of the building envelope. In contrast, tracer-gas techniques typically measure air exchange under naturally occurring conditions; such methods are fundamentally tied to mass balance considerations, using inert tracers that are not normally present in the indoor or outdoor atmosphere. As summarized in Table I, there are two pressurization methods (fan pressurization and AC pressurization) and three tracer-gas methods (concentration decay, constant injection, and constant concentration) that are in general use.

Pressurization Techniques

The fan-pressurization method has been designated as standard practice by the American Society for Testing and Materials.[2] In this method, leakage characteristics of a structure are measured under controlled pressurization and depressurization. A range of positive and negative indoor-outdoor pressure differences is produced by using a variable-speed reversible fan, which is temporarily installed in an entry doorway. The fan can move large volumes of air into or out of the structure. At a constant indoor-outdoor pressure difference, all air flowing through the fan is compensated by equal flow through available openings in the building envelope. When all controllable external openings such as windows and doors are closed, the resulting data can be used to evaluate the leakage characteristics of the building envelope and thus form the basis for comparisons of relative tightness.

The fan-pressurization data can be used to determine the effective leakage area, which is an estimate of the aggregate size of the openings through which infiltration may occur at rates determined by a variety of influences; effective leakage area should not be confused with the air exchange rate. Effective leakage area can be determined for any measured or interpolated pressure difference, but it has become common practice to use the measured or calculated air leakage rate at 50 Pa pressure difference as a reference point for comparisons of air tightness in buildings.[3]

The AC pressurization method[4] creates an oscillating pressure difference across the building envelope using a piston or bellows drive to alter the indoor volume at a known frequency. The amplitude and phase of the indoor pressure with respect to the volume drive are related to the tightness of the building envelope. By operating in regimes of pressure difference that are of the same magnitude as the weather-induced pressure differences that drive natural air exchange, application of the technique circumvents the need for the large airflows that accompany fan pressurization tests.

Tracer-Gas Techniques

The concentration-decay technique (also called tracer-gas dilution) has been designated as a standard practice by the American Society for Testing and Materials.[5] In this technique, a small amount of tracer gas is injected into the indoor airspace and thoroughly mixed. Indoor concentrations "decay" with time as the exfiltrating air removes the tracer. The general procedure involves releasing tracer gas at one or more points in sufficient quantities to produce useful initial concentrations. The method of release and quantities involved depend on the internal volume of the structure, the configuration of the air-handling system, estimates of allowable versus useful concentrations, and the sensitivity of the detection system.

An alternative to the concentration-decay method is the constant-injection method. Rather elaborate systems to constantly release and monitor indoor tracer-gas concentrations, such as that developed and tested by Condon et al.,[6] have been used. A constant-injection technique has been developed and tested at the Brookhaven National Laboratory using diffusion-based release and sampling of perfluorocarbon tracers (PFTs).[7] In this method, a bullet-sized container releases the PFT at a constant rate. Sampling is carried out using a 4-mm diameter capillary adsorption tube (CAT) that collects the tracer by diffusion. Four different PFTs are available to measure flows among multiple zones of structure.

Sampling with PFTs may proceed for periods as short as a day, or may be extended over a number of weeks. Recommended mixing time prior to sampling is 8 h. This delay could present a problem in logistics because the procedure would require a return visit or the involvement of a resident to initiate sampling at the proper time. However, in situations where this delay period is very small compared to the total sampling period (e.g., sampling period of about a week), sources and samplers can be activated simultaneously without significantly affecting results.

In the constant-concentration approach, automated equipment is required to continually analyze tracer-gas concentrations and, based on losses due to air exchange, inject additional tracer to maintain a constant concentration. The constant-concentration technique offers an advantage over other single-tracer techniques in that air exchange rates can be measured simultaneously for individual zones within a building. As reviewed in Lagus and Persily,[8] this method has been successfully used in a variety of buildings with as many as 10 zones.

Although this technique is useful for evaluating air exchange rates with the outdoors on a zone-specific basis, the air flows between zones cannot easily be resolved. Furthermore, automating the constant-concentration technique requires rapid tracer analysis and feedback for compensatory injection. Small fans are often incorporated to promote mixing within the zone; however, if fan-assisted systems are used while monitoring pollutants, the data may not fully reflect normal conditions for some pollutants.

EXPERIMENTAL METHODS

During the study, 157 residences in North Central Texas were monitored for indoor air quality over a 9-week period between January and March 1985. Procedures for selecting residences and monitoring indoor air quality are described in a companion paper.[9] Air exchange under naturally occurring conditions was monitored by two tracer-gas techniques--the concentration-decay method, with sulfur hexafluoride (SF_6) as the tracer gas, and the constant-injection method with PFTs. Building tightness was measured by the fan-pressurization method. Approximately 30 percent of the 157 study homes were monitored for air exchange and 50 percent were measured for building tightness.

Tracer Gas

In this study, a relatively simple concentration-decay method reported by Harrje et al.[10] was adapted by replacing manual sample-collection methods with automated syringe samplers. The samplers used are packaged in racks of nine with a programming device that controls the rate at which each syringe sequentially draws a sample. The quantity of SF_6 required to achieve a target concentration of 1 part per million (ppm) was calculated based on the measured house volume. Following manual injection of SF_6, the syringe rack was programmed to draw integrated samples over sequential

45-minute intervals (6.75 hours in total). In most residences, this procedure was used on two separate occasions. The usual sampling location was near the geometric center of the residence. The impacted syringes were returned to GEOMET's laboratory for analysis by gas chromatography.

The accuracy of this SF_6 sampling approach was assessed in GEOMET's research houses[11] by colocating several syringe racks with a continuous SF_6 measurement system and comparing the dilution measured by the two systems. An illustrative validation result is shown in Figure 1 for four colocated syringe racks programmed to draw integrated SF_6 samples over periods of 30, 45, 60, and 75 minutes per syringe, respectively. As indicated in the figure, the exponential dilution of SF_6 concentrations was represented quite similarly by the integrated and continuous systems, apart from some slight initial differences. Calculated air infiltration rates for each rack agreed with those calculated for the continuous system within ±10 percent.

For the constant-injection method, only one type of PFT source was typically used in each home because nearly all study residences were one-story homes with relatively small living areas. Sources were spatially arrayed in accordance with specifications developed by the Brookhaven National Laboratory (BNL). One CAT sampler was usually placed near the geometric center of the home; in selected cases, field blanks or multiple colocated samplers were used for quality-control purposes. Information on sampling start and stop times, house volumes, and average indoor temperatures during sampling was forwarded with the exposed CAT samplers to BNL. The usual sampling duration was 5 days.

Fan Pressurization

Fan-pressurization tests with a calibrated blower door were scheduled after monitoring was completed. Residences were tested with all doors, windows, and fireplace dampers closed and with furnaces off. If baseline indoor-outdoor pressure differentials were not steady due to ambient wind conditions, the test was rescheduled. Testing was performed in pressurized and depressurized modes at 10, 17, 25, 35, 50, and 62.5 Pa; for houses that could not be pressurized to the highest target values, the maximum attainable value was used as a testing point.

The observed flow rates at each pressure difference were fitted to a general equation by least-squares techniques, and the resultant equation was used to predict the flow rate at 50 Pa. This procedure was used separately for the pressurization and depressurization results on a house-by-house basis. Predicted flow rates were divided by house volume to obtain predicted air changes per hour (ACH) at 50 Pa for each house.

Questions to Occupants

Prior to the selection of residences for monitoring, a 4-page screening survey was administered to occupants. Three of the questions (Figure 2) concerned building-tightness factors. The first two questions were phrased similarly to ones used in the Department of Energy's Residential Energy Consumption Surveys or the Census Bureau's Annual Housing Surveys. The third question, somewhat more subjective, was designed to obtain occupants' perceptions concerning the relative draftiness of the structure. At the conclusion of monitoring, occupants were asked how frequently doors or windows were left open during the monitoring period.

Two indices of house tightness were developed based on the responses to these questions:

- STMCAULK--obtained by summing scaled responses to the first two questions; each response was scaled as a 2 for all or most doors/windows, 1 for some, and 0 for few or none.
- DRAFTOT--obtained by summing scaled responses to three parts of the third question--drafts around doors (2 = often, 1 = sometimes, 0 = rarely), around windows (2,1,0) and in any other place (2 if mentioned, 0 if not mentioned); none of the respondents indicated that drafts around wall outlets were noticeable.

Thus, STMCAULK was represented by a scale from 0 to 4, with a higher scale value indicating a "tighter" home, and DRAFTOT was represented by a scale from 0 to 6, with a higher value indicating a "looser" home.

MEASUREMENT RESULTS

Blower-door tests were performed in 77 residences; valid results in both the pressurized and depressurized modes of testing were obtained for 72 of the residences. The distributions of predicted ACH at 50 Pa were quite similar for the two modes--a mean ± standard deviation of 26.9±13.9 ACH for pressurization results and 26.4±11.1 ACH for depressurization results.

The extent of agreement between the two testing modes on a house-by-house basis is shown in Figure 3 in relation to a line of one-to-one correspondence. Two potential outliers that are circled in the figure have pressurization/depressurization ratios greater than 2 or less than 0.5. The R^2 value (proportion of variance about the mean for one mode that was explained by the other) was 0.68; with removal of the two potential outliers, the R^2 value increased to 0.78. Although there was a fairly high degree of correspondence between pressurization and depressurization results, the extent of scatter about the line of one-to-one correspondence was noticeably larger for results above 20 to 30 ACH; possible reasons for the increased scatter are being explored.

During the period (January to March 1985) when air exchange was measured with tracer-gas techniques, average weekly outdoor temperatures ranged from 19 °F to 61 °F. Valid SF_6 measurement results were obtained from 40 homes and valid PFT results from 37 homes; there were 32 homes with valid results for both methods. An assessment of the correspondence between the two methods of measuring air infiltration rates was based on 24 homes in which windows or doors were rarely opened during monitoring. The extent of agreement between the two methods, shown graphically in relation to a line of one-to-one correspondence (Figure 4), was quite good. The mean ± standard deviation was 0.81 ± 0.36 air changes per hour (ACH) based on SF_6 and 0.75 ± 0.39 ACH based on PFT; in only 2 cases out of 24 did the results of the two methods disagree by as much as 0.4 ACH.

The R^2 value for SF_6 versus PFT results was 0.72. The line of best fit relating the results from the two methods is as follows:

$$\text{ACH } (SF_6) = 0.22 + 0.80 \times \text{ACH (PFT)} .$$

Thus, the two methods provided nearly identical estimates at 1.0 ACH; above 1.0 ACH, the SF_6 method tended to yield somewhat lower estimates; below 1.0 ACH, the PFT method gave somewhat lower estimates.

The SF_6 and PFT results were also analyzed for correlation with blower door results (predicted ACH at 50 Pa, or ACH50, based on test results in the depressurized mode), AVGDIFF (indoor minus outdoor temperature), average windspeed measured at nearby airports, and the two indices of house tightness discussed previously. The matrix of correlation coefficients among air infiltration results, blower door results, and the questionnaire indices is given in Table II. Both types of air infiltration results were highly and positively correlated with blower door results and were correlated with all other factors to a lesser extent but in the expected direction. Most interestingly, the subjectively derived DRAFTOT index correlated better with SF_6, PFT, and blower-door results than did the STMCAULK index.

In contrast to Persily and Grot's results,[12] infiltration results did not correlate with windspeed, perhaps because the wind measurements were made at remote locations. ACH50 and AVGDIFF were uncorrelated, representing an ideal situation for assessing their independent contributions to air infiltration. Air infiltration measurements were regressed against ACH50, AVGDIFF, STMCAULK, and DRAFTOT to determine the predictability of air infiltration results. The predictive equations, determined by applying stepwise regression methods and retaining only statistically significant predictors ($p < 0.1$), were as follows (standard errors of regression terms in parentheses):

$$\begin{array}{llllll} \mathrm{SF_6} = & 0.127 + & 0.016 \times \mathrm{ACH50} + & 0.007 \times \mathrm{AVGDIFF} & & \\ & (0.105) & (0.002) & (0.003) & & (R^2 = 0.76). \end{array}$$

$$\begin{array}{llllll} \mathrm{PFT} = & 0.263 + & 0.014 \times \mathrm{ACH50} + & 0.006 \times \mathrm{AVGDIFF} - & 0.084 \times \mathrm{STMCAULK} & \\ & (0.143) & (0.003) & (0.003) & (0.041) & (R^2 = 0.66). \end{array}$$

Thus, both measures of air infiltration could be predicted with a fairly high degree of accuracy. ACH50 was the major predictor for both SF_6 and PFT measures of air infiltration; without this variable, only 21 percent of the SF_6 variation and 32 percent of the PFT variation could be explained. An interactive term for ACH50 and AVGDIFF (i.e., ACH50 x AVGDIFF) was later included as a candidate predictor variable, but this term did not add significantly to the explanatory power of either of the above equations.

CONCLUSIONS

Based on the results presented in this paper, the following conclusions or inferences can be drawn:

- The two methods used in the study for measuring residential air infiltration rates (PFTs and SF_6 syringe samples) gave very comparable results; although the SF_6 technique requires a field technician to deploy and retrieve samplers, the turnaround time for laboratory analysis is much less than currently exists for PFTs. If other aspects of field monitoring require the presence of technicians, then syringe sampling can be a very cost-effective method.

- In this study, air infiltration rates for 23 homes could be predicted fairly accurately from blower-door results and indoor-outdoor temperature differences; however, these results are for a rather limited range of residential types with measurements performed only during a single season.

- Occupants' perceptions of the relative draftiness of a residence may be as or more important than structural details such as storm windows, caulking, or weatherstripping as correlates of air leakage or infiltration.

ACKNOWLEDGMENT

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Table I. Summary of pressurization techniques for measuring building tightness and tracer-gas techniques for measuring air exchange.

Technique	Operating principle
Pressurization	
Fan pressurization	A constant pressure difference is created across the building envelope using a fan. Pressure-flow relationships for positive and negative pressure differences are evaluated to determine building tightness.
AC pressurization	An oscillating pressure difference is created across the building envelope using a piston to vary the indoor volume. Relationships between piston cycling and pressure cycling in the indoor airspace are evaluated to determine building tightness.
Tracer-gas	
Concentration decay	A small amount of tracer gas is introduced and mixed into the indoor airspace. The resulting decay of tracer gas concentration indoors, due to entry of tracer-free outdoor air, is related to the air exchange rate.
Constant injection	Tracer gas is released to the indoor airspace at a constant rate. Changes in indoor concentration are related to tracer release rate and air exchange rate.
Constant concentration	Tracer-gas release is controlled to maintain a constant concentration. Air exchange rate is related to the volume of tracer released.

Table II. Matrix of Pearson correlation coefficients among air infiltration results (SF$_6$ and PFT), blower door results (ACH50), and questionnaire indices of house tightness (STMCAULK and DRAFTOT).

	SF6	PFT	ACH50	AVGDIFF	STMCAULK	DRAFTOT
SF6	1.0	0.85*	0.81*	0.34	-0.12	0.32
PFT		1.0	0.74*	0.22	-0.38	0.42*
ACH50			1.0	0.03	-0.14	0.43*
AVGDIFF				1.0	0.13	0.04
STMCAULK					1.0	-0.25
DRAFTOT						1.0

* Statistically significant at the 0.05 level (two-sided test).

NOTE: All coefficients based on 24 cases except those involving ACH50 (23 cases).

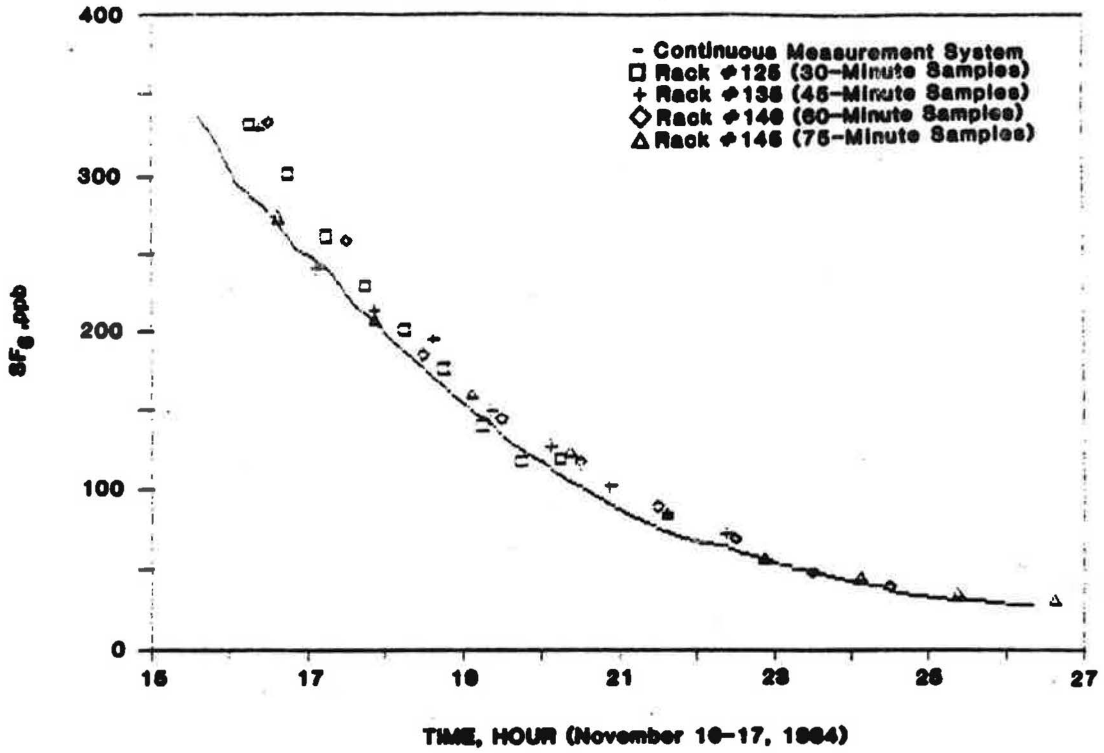


Figure 1. Comparison between automated syringe sampling system (four different sampling rates) and continuous system for SF_6 measurement.

1. How many of your doors and windows have storm doors and windows, double-glazed glass, or other protective coverings such as plastic or shutters?

   [ ] All or most [ ] Some or about half [ ] Few or none

2. During the past 2 years, has any caulking or weatherstripping been applied to your doors or windows? [ ] Yes [ ] No

   (If yes) For how many of the doors or windows was this done?

   [ ] All or most [ ] Some or about half [ ] Few or none

   What is the current condition of the caulking or weatherstripping?

   [ ] Basically intact [ ] Cracked or peeling [ ] Don't know

3. During times when it is windy or cold outside, do you notice or feel drafts around .....

   a. Doors? [ ] Often [ ] Sometimes [ ] Rarely

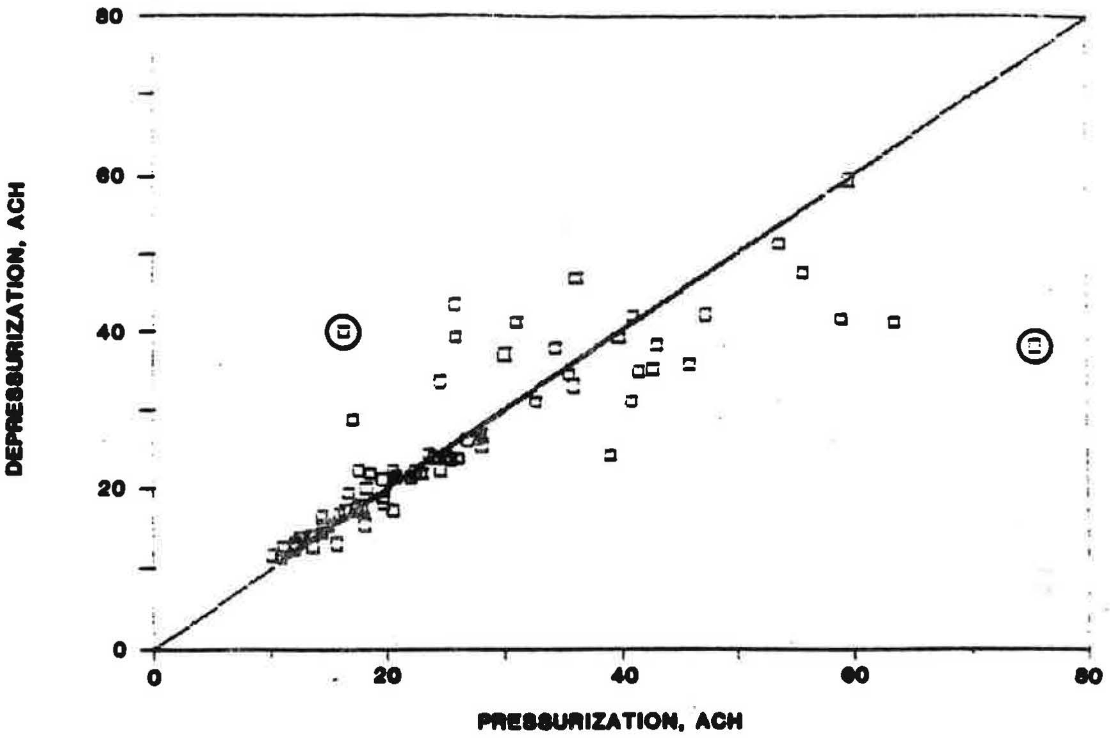
   b. Windows? [ ] Often [ ] Sometimes [ ] Rarely

   c. Wall outlets? [ ] Often [ ] Sometimes [ ] Rarely

   d. Any other place? (Specify) ________________________

   ____

Figure 2. Three types of questions concerning building tightness.



Note: The two cases that are circled represent possible outliers.

Figure 3. Correspondence between pressurization and depressurization results (predicted ACH at 50 Pascals) of blower-door tests for 72 homes.

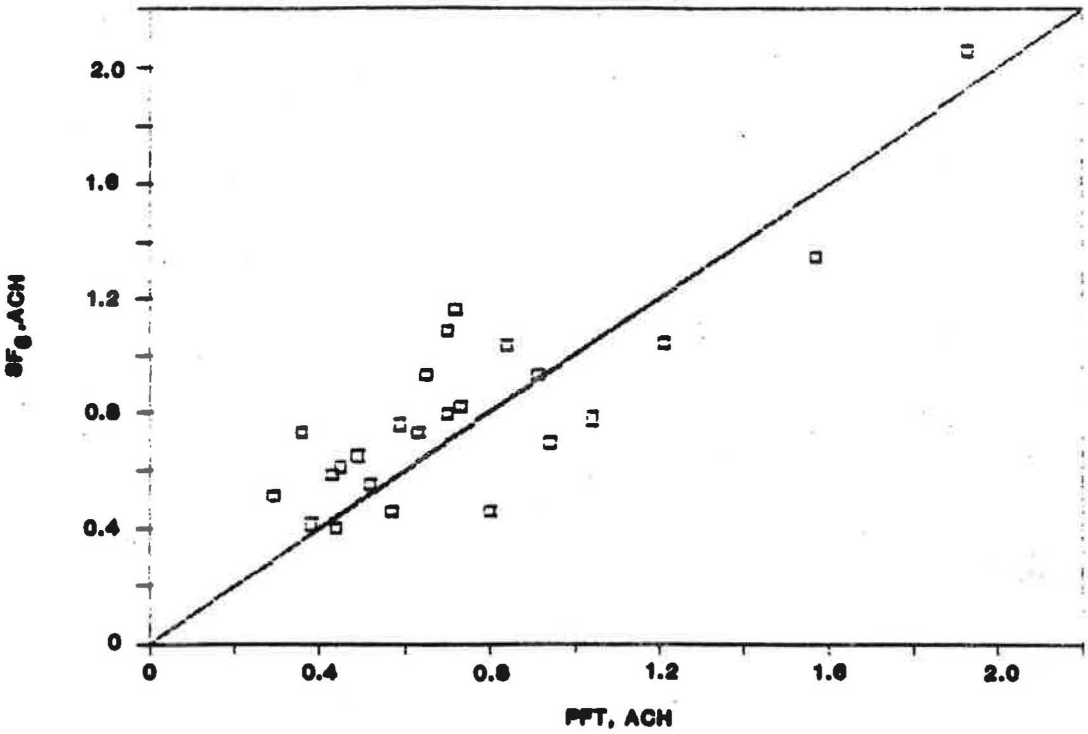


Figure 4. Correspondence between SF_6 and PFT measurements of air infiltration rates for 24 homes.