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AIR LEAKAGE MEASUREMENTS OF AN UNPARTITIONED MOBILE HOME

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ABSTRACT

Air exchange rates, $I(h^{-1})$, of an unpartitioned mobile home were measured at various indoor-outdoor temperature differences, $\Delta T(K)$, using SF_6 tracer in an environmental chamber, and found to be lower than for conventional buildings but similar to other mobile homes. There was little scatter from the regression equation $I = 0.0182 + 0.0118 |\Delta T|$, with relative standard errors of the first and second coefficients of 62 and 2.5%, respectively.

A fan depressurization experiment was also performed, and yielded a flow coefficient of $C = 1.64 \times 10^{-4}$ $m/s{\cdot}Pa^{0.65}$, which is also comparable to that of a previously measured mobile home. It was further found that:

(1) For $I = 0.24$ h^{-1}, no SF_6 could be detected in the environmental chamber even after five hours, but when $I = 9$ h^{-1} for more than five minutes, the tracer gas method could not be used accurately in the environmental chamber even with exhaust fans operating;

(2) The standard error is useful for monitoring whether sufficient concentration measurements were taken at each step;

(3) An air bag sampling technique appeared as good as the conventional monitoring method for determining infiltration rate;

(4) Reported intercepts of regression equations vary greatly from building to building, and it may be difficult to analyze the significance;

(5) The possibility that $I = 0$ h^{-1} at $\Delta T = 0$ K cannot be excluded.

Keywords: Air leakage measurements; environmental chamber; fan pressurization; mobile home; sulfur hexafluoride; tracer gas.

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1. INTRODUCTION

There are few existing measurements of air leakage characteristics of mobile homes [1,2] even though such information is important for predicting energy use, and indoor air pollutant concentrations and their health effects. As part of an ongoing study of the thermal characteristics of a mobile home, infiltration rate was measured by tracer gas, and envelope permeability by fan depressurization. The absence of wind made it possible to accurately measure the temperature dependence of the air exchange rate in isolation, and to compare it with that of other structures.

2. TEST METHODS

2.1 TRACER GAS METHODS

Infiltration rates of an unpartitioned mobile home were measured in an environmental chamber at the Center for Building Technology, National Bureau of Standards, Washington, using the sulfur hexafluoride (SF_6) tracer gas technique described elsewhere [3]. The mobile home contains aluminum-backed fiberglass insulation with thermal resistance 1.9 $m^2 \cdot K/W$ (R-11) in the walls and floor and 3.3 $m^2 \cdot K/W$ (R-19) in the ceiling. The mobile home is 11.989 m long, 2.856 m wide and 2.438 m high, for a total volume of 83.48 m^3 and a total surface area of 140.87 m^2.

Four cm^3 of SF_6, calculated to give an initial concentration of about 50 ppb, were injected into the mobile home. A fan was run in the mobile home throughout each experiment to mix tracer gas with air. To further ensure adequate mixing, SF_6 monitoring, using an electron capture detector [3], was started about one-half hour after injection. Sulfur hexafluoride concentration was monitored for at least one hour and infiltration rate was calculated from the rate of tracer gas dilution:

$$I = -\frac{60}{t} \ln(c/c_o) \tag{1}$$

where:

I = infiltration rate (h^{-1})
t = time (min)
c = SF_6 concentration at time t min
c_o = SF_6 concentration at time 0 min
(c and c_o are expressed in mutually consistent arbitrary units.)

A pocket calculator was programmed to linearly fit the natural logarithm of concentration with time (min) by least squares analysis; the infiltration rate is 60 times the negative of the slope of the regression line, as can be deduced from equation (1).

Standard errors of the regression coefficients of an equation of the form:

$$y = a + bx$$

were calculated [4] by the equations:

$$s_a = \text{RMS}\left(1 + \frac{\mu_x^2}{\sigma_x^2}\right)^{1/2} \quad (2a)^*$$

$$s_b = \text{RMS}/(N\sigma_x) \quad (2b)^*$$

where:

s_a, s_b = standard errors of a and b respectively

N = number of measurements

$$\text{RMS} = \left(\frac{1}{N}\sum_{1}^{N}(y_i - a - bx_i)^2\right)^{1/2}$$

$$\mu_x = \frac{1}{N}\sum_{1}^{N} x_i$$

$$\sigma_x = \left(\frac{1}{N}\sum_{1}^{N} x_i^2 - \mu_x^2\right)^{1/2}$$

The correlation, R^2, is given by:

$$R^2 = b^2 \frac{\sigma_x^2}{\text{RMS}^2} \quad (3)$$

Instruments were located outside of the mobile home (and also outside the chamber for low chamber temperatures). A small tube was passed out a window to the detector and the window was sealed with tape to prevent any induced air leakage. SF_6 was injected through the tape and once the experiment began the

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* If equally spaced intervals are used, then:

$$s_a = \left(\frac{2(2N-1)}{N(N+1)}\right)^{1/2} \text{RMS} \quad (\approx 2N^{-1/2}\,\text{RMS}) \quad (2a')$$

$$s_b = \left(\frac{12}{(N-1)N(N+1)}\right)^{1/2} \text{RMS}/\Delta x \quad (\approx (12/N^3)^{1/2}\,\text{RMS}/\Delta x) \quad (2b')$$

where:

Δx = length of each interval

$x_i = (i-1)\Delta x$, $i = 1, \ldots, N$

doors remained closed. Lights were kept off during the entire experiment to prevent heat build-up. An average of six mobile home and twelve chamber thermocouple readings were monitored at approximately ten-minute intervals during each experiment.

In addition, air bag samples of the mobile home and environmental chamber were taken for about five minutes, as described by Grot [5], in order to 1) compare that technique of air exchange rate determination to direct SF_6 monitoring, and (2) detect any SF_6 in the chamber.

2.2 FAN DEPRESSURIZATION

A depressurization test was conducted with the fan and duct apparatus as described by Teitsma and Peavy [7]. It consisted essentially of an inline fan and duct. A commercial pitot-static assembly was mounted midway in the duct to monitor flow rate. The outlet end of the duct was sealed into the doorway using a wooden board, polyethylene film and tape. Pressurization was not done because of lack of space in the environmental chamber. A magnehelic gage (range 0.25 in of H_2O (62 Pa)) was used to measure the pressure drop across the assembly of pitot-static tubes in a duct of cross-sectional area 0.929 m^2 (1 ft^2), and a magnehelic gage (range 0.50 in of H_2O (124 Pa)) was used to measure the indoor-outdoor pressure difference. Each pressure difference remained nearly constant during any experiment. The flow rate through the duct was controlled by blocking selected fractions of the fan outlet area. Fan flow rate was calculated [6] by the equation:

$$Q = 1.29A \cdot \Delta P_g^{1/2} \quad (4)$$

where:

Q = flow rate, m^3/s
A = cross-sectional area of the flow monitor, m^2
ΔP_g = pitot-static gage pressure difference, Pa

(When Q is measured in cfm, A in ft^2 and ΔP_g in inches of H_2O, the constant 1.29 in equation (4) is replaced by 4005.)

An experiment was also done to compare flow rates determined by pressure difference and tracer gas techniques; the indoor air temperature in the mobile home remained nearly constant at 20.0°C and the chamber temperature at 17.3°C during this experiment.

The best fit between Q and ΔP [6] was obtained for $n = 0.48$ in the equation:

$$Q = CA(\Delta P)^n \quad (5)$$

where:

C = flow coefficient ($m/s \cdot Pa^n$)
A = surface area (m^2)

ΔP = environmental chamber-mobile home pressure difference (Pa)
n = flow exponent

C was calculated for $n = 0.5$, and also for $n = 0.65$ since n is often near this value [8].

A surface area of 138 m^2 was used for the mobile home (after subtractin 3 m^2 for the film and tape holding the fan apparatus in place).

3. RESULTS

3.1 INFILTRATION MEASUREMENTS

Measurements were done to relate infiltration rate and indoor-outdoor temperature difference. The data are summarized in Table 1 and displayed graphically in Fig. 1. Results of detailed experiments done at various indoor-outdoor temperature differences are shown in Fig. 2 to 6. The regression line in Fig. 1 was determined by ignoring temperature difference standard deviations, and the data points corresponding to 2.14 and 2.16 K. The temperature difference error bands of these last two points are much greater than for the other point in the vicinity, 0.56 K, and the regression line passes through the boxes containing these points in any case. The fit is excellent, with correlation $R^2 > 0.99$. The equation describing the regression line is given by:

$$I = 0.0182 + 0.0118\,|\Delta T| \tag{6}$$
$$s_a = 0.011\ h^{-1}$$
$$s_b = 0.0003\ h^{-1}/K$$

where:

I = air exchange rate (h^{-1})
T_{in} = mobile home air temperature (°C)
T_{out} = environmental chamber air temperature (°C)
$\Delta T = T_{in} - T_{out}$

In the experiment shown in Fig. 2, Grot's air bag method [5] for determining air exchange rate was compared with direct monitoring of tracer gas. During this experiment a window was open and a fan operated in the interior of the mobile home. Air bag samples were taken in the mobile home at about 23 and 89 min. The air exchange rate was calculated to be 0.26 h^{-1}, or 15% lower than the air exchange rate of $0.306 \pm 0.014\ h^{-1}$ calculated from the regression line in Fig. 7.

3.2 UNCERTAINTY OF THE AIR EXCHANGE RATES

It was generally found that 4 or 5 concentration measurements at 10 min intervals sufficed to stabilize the linear regression correlation coefficient and calculated infiltration rate standard error, or to reduce the relative error to 10%.

The calculated relative standard error and correlation coefficient can be monitored after each concentration measurement. The former appeared to be a more sensitive measure of dispersion since it frequently continued to decrease with additional data after the latter had stabilized. Since these measures serve as predictors of future concentration measurements, the experiment can be terminated after they reach desired levels or stabilize. Table 2 shows how these parameters changed during the course of the experiment shown in Fig. 6. The worst case was chosen for illustration; in another experiment (Fig. 7), for example, a correlation of 0.99 was achieved by the third measurement. When the time interval is small, four values should probably be taken to assure accuracy. The reason the air bag method [5] is capable of yielding accurate results with only two concentration measurements is probably that they are taken a long time apart. Equation (2b') of the note in the test methods section suggests that large time intervals can reduce the number of concentration measurements required to achieve a specified degree of accuracy.

3.3 FAN DEPRESSURIZATION

Fan depressurization data are listed in Table 3 and plotted in Fig. 8. The best fit was obtained using either of the relationships:

$$Q = 0.0432(\Delta P)^{0.5} \tag{7a}$$

or:

$$I = 1.86(\Delta P)^{0.5} \tag{7b}$$

However, if $n = 0.65$ is assumed, the fit is still excellent except for the pressure difference measurement corresponding to the lowest flow rate. For $n = 0.65$, the equations became:

$$Q = 0.02265(\Delta P)^{0.65} \tag{7a'}$$

or:

$$I = 0.9766(\Delta P)^{0.65} \tag{7b'}$$

Thus there is no large disagreement with Shaw and Tamura's suggested flow exponent of $n = 0.65$ [8]. In order to facilitate comparison, flow coefficients were calculated by fitting the data of the present paper and from Teitsma and Peavy [7] to equation (5) with $n = 0.65$. (The best fit in the latter paper was obtained for $n = 0.60$.)

Flow coefficients of 1.64×10^{-4} and 2.26×10^{-4} m/s•Pa$^{0.65}$, respectively, were obtained. They are comparable with Tamura's [9] calculated flow coefficients of 1.1×10^{-4} and 4.6×10^{-4} m/s•Pa$^{0.65}$ for two single-story houses.

3.4 THE PRESENCE OF SF_6 IN THE ENVIRONMENTAL CHAMBER

In the experiment shown in Fig. 4 ($I = 0.24\ h^{-1}$), air bag samples were taken from the chamber to detect any SF_6, but even after 5 hours none was found. In the experiment described in Fig. 8 and 9, the air exchange rate measured by tracer gas declined from 28 to 12 h^{-1}, compared to 16 h^{-1} when measured by Pitot-static flow monitoring at $\Delta P = 81.9$ Pa, suggesting SF_6 accumulation in the environmental chamber. In another experiment (data not shown) enough SF_6 accumulated after 5 min at an induced air exchange rate of 9 h^{-1} at 19.7 Pa to make it impossible to use the environmental chamber for tracer gas measurements.

4. DISCUSSION

The unpartitioned mobile home appeared to be an extremely tight structure. Air exchange rates ranged from 0.03 h^{-1} for $|\Delta T| = 1$ K to 0.4 h^{-1} for $|\Delta T| = 29$ K with windows and doors closed, a temperature dependence comparable to partitioned mobile homes [1,2], an experimental masonry block building [10] and to other buildings with tightened envelopes [11-13] (Table 4). The mobile home studied here seems to be typical of mobile homes in envelope tightness, judging from the limited number of studies. This raises questions about occupant exposure to air contaminants, most notably formaldehyde [14].

The flow coefficient of the mobile home surfaces of the present report was three quarters that measured by Teitsma and Peavy [7]. The flow exponent giving the best fit was $n = 0.5$ but $n = 0.65$ also gives excellent fit.

Table 4 contains several anomalous results. The mobile home described here seems half as leaky as that described by Hunt et al.[1] at $\Delta T = 0$ K while it is twice as sensitive to changes in $|\Delta T|$. The present mobile home is about as leaky as the experimental masonry building (also an unpartitioned single chamber) at $\Delta T = 0$ but about 10 times as sensitive to changes in $|\Delta T|$[10]. A wooden house retrofitted to conserve energy seemed to become more leaky at $\Delta T = 0$ K and about 17% more sensitive to wind-induced infiltration (which is easily explainable by experimental error) while becoming half as sensitive to ΔT-induced infiltration [11]. A caulked mobile home seemed to be less sensitive to wind-induced infiltration and more sensitive to ΔT-induced infiltration than one that was covered with continuous sheathing board [2]. While this seeming independence of I_o, b and c may have physical significance, the work described here suggests another possible explanation, namely that estimates of I_o are highly uncertain while b is relatively certain. In this report, I_o and b were estimated to have relative calculated standard errors of 62 and 2.5% respectively. This predicts that I_o might be substantially changed by further data points while b would not.

Unfortunately, statements about uncertainty of the coefficients are rare in the literature, but if the uncertainties are similar to those reported here, the apparent anomalies in the relative sizes of I_o might disappear. The calculated standard errors used here do not depend on errors or variation in temperature and infiltration rate during each experiment, but only on deviation from linearity. This is because temperature can be precisely controlled and measured. Wind speed, on the other hand, fluctuates so measurement error may have to be considered.

The absence of wind in the environmental chamber eliminated much scatter, and enables one to begin to answer the two related questions: 1) Does I "really" depend linearly on $|\Delta T|$? and 2) Is I_o "really" greater than 0 h^{-1}? Linearity has been questioned on theoretical grounds, but rarely has inclusion into the regression analysis of nonlinear terms improved fit for ordinary temperature ranges [15]. Use of nonlinear models is summarized in reference 16. This report suggests adequacy of the linearity assumption concerning $|\Delta T|$ at least, since a correlation $R^2 > 0.99$ was obtained between the data and the regression line. Since there was no wind in the environmental chamber, there is no conflict with Sinden's argument that I is subadditive in $|\Delta T|$ and wind speed [17]. The second question cannot be answered conclusively but I_o doesn't differ from 0 h^{-1} at the 5% level of significance (calculation not shown).

Another aspect of infiltration measurements studied was use of air bag sampling [5]. Infiltration rate measured by that method [5] was in good agreement with the usual tracer gas technique. The air bag method eliminates the need to transport and set up heavy equipment and makes possible otherwise impractical measurements and large numbers of air exchange measurements.

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Table 1. Summary of Infiltration Rate Measurements

Fig.	T_{in} (σ), °C	T_{out} (σ), °C	ΔT (σ), K	I (s_I), h^{-1}
6	19.5 (0.02)	18.9 (0.01)	0.56 (0.02)	0.0265 (0.0051)
3	13.8 (1.6)	15.9 (2.6)	-2.14 (1.85)	0.0308 (0.0026)
2	25.4 (0.3)	23.3 (1.1)	2.16 (1.35)	0.0571 (0.0060)
3	26.2 (0.5)	13.7 (0.4)	12.56 (0.85)	0.164 (0.004)
4	18.0 (0.9)	-1.0 (0.3)	19.03 (0.9)	0.241 (0.003)
5	17.7 (0.1)	-11.4 (0.1)	29.14 (0.15)	0.363 (0.005)

Table 2. Correlation Coefficient and Standard Error Monitoring Corresponding to the Experiment in Fig. 6

Measurement	Air exchange rate, $I(S_I)$, h^{-1}	Correlation coefficient, R^2	Relative calculated standard error, S_I/I
1	---	---	---
2	0.0153 (---)	---	---
3	0.0126 (0.0136)	0.221	1.08
4	0.0159 (0.0058)	0.652	0.365
5	0.0334 (0.0073)	0.807	0.219
6	0.0233 (0.0072)	0.636	0.309
7	0.0219 (0.056)	0.690	0.254
8	0.0265 (0.0051)	0.768	0.194

Table 3. Fan Depressurization Measurements

Condition	Q m^3/s	Q cfm	$\lvert\Delta P\rvert$ Pa	$\lvert\Delta P\rvert$ in
fan totally covered	0.224	474	24.1	0.100
" 3/4 "	0.378	800	81.9	0.329
" 3/4 "	0.383	811	80.1	0.322
" 1/2 "	0.447	948	107.5	0.432
" uncovered	0.482	1021	123.2	0.495

Table 4. Infiltration Rate Dependence on Temperature and Wind Speed

$$I = I_0 + b|\Delta T| + cV$$

where V = wind speed (m/s)

Building	$I_0 (h^{-1})$	$b (h^{-1}/K)$	$c (h^{-1}/m \cdot s^{-1})$	Reference
unpartitioned mobile home	0.018	0.012	*	present report
partitioned mobile home	0.036	0.006	*	1
partitioned mobile homes:				2
caulking**	-0.00835**	0.0103	0.036	
ontinuous sheathing board**	0.0159	0.0065	0.0172	
experimental masonry block+	0.016	0.0009	*	10
wood frame: pre-retrofit	0.11	0.018	0.044	11
post-retrofit	0.22	0.009	0.051	
10 electrically heated	0.25	0.015	0.048	12
"tightly constructed" ++	0.10	0.011	0.027	13
"loosely constructed" ++	0.10	0.022	0.067	13

* No wind in the NBS environmental chamber

** In the original paper the relation given was $I = 0.0635 + 0.0103\ |\Delta T| + 0.018\ V^2 + 1.53 \times 10^{-4}\ \Delta T \cdot V^2$ for the first mobile home and $I = 0.0503 + 0.0065\ |\Delta T| + 0.0086\ V^2 + 0.89 \times 10^{-4}\ \Delta T \cdot V^2$ for the second. For comparability, the coefficients in the table were computed by neglecting the $\Delta T \cdot V^2$ terms and minimizing the difference between the expression in the original paper and one linear in V for V = 2 m/s. The small negative value of I_0 for the first home is an artifact of this procedure.

\+ Winter only; in original paper the second order relationship, $I = 0.017 + 0.0005\ |\Delta T| + 0.00001\ |\Delta T|^2$ was derived, but a linear fit was recomputed here.

++ Typical values.

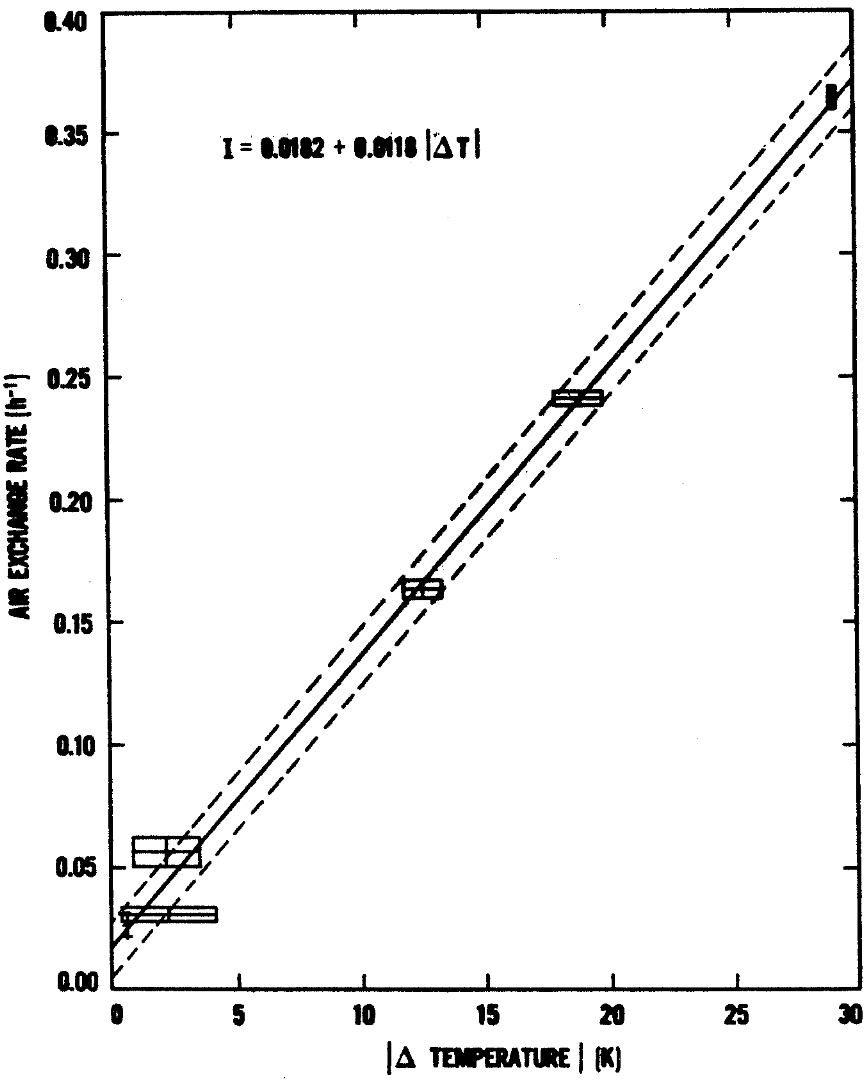

Figure 1. Air exchange rate dependence on absolute value of indoor-outdoor temperature difference. (Data are summarized in Table 1.) The width of the box around each point is two calculated standard deviation units ($\sigma_{\Delta T}$); the height is two calculated standard error units (S_I). The dashed lines represent the solid regression line modified by adding (top) and subtracting (bottom) one calculated error unit to each coefficient of the regression equation.

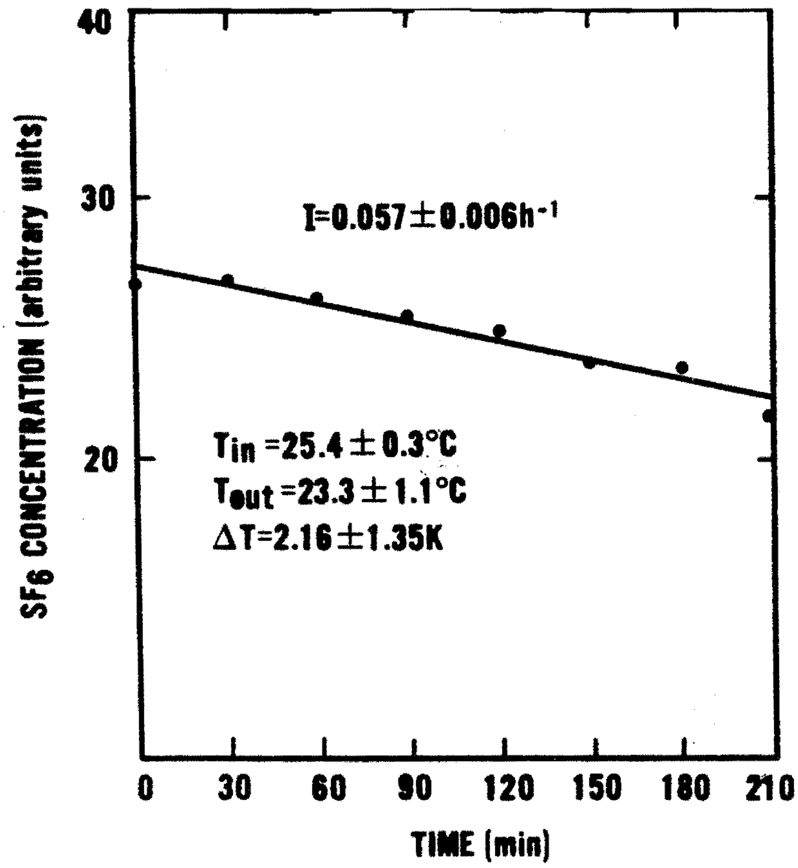

Figure 2. Decay of tracer gas concentration over time at an average indoor-outdoor temperature difference of 25.4 K.

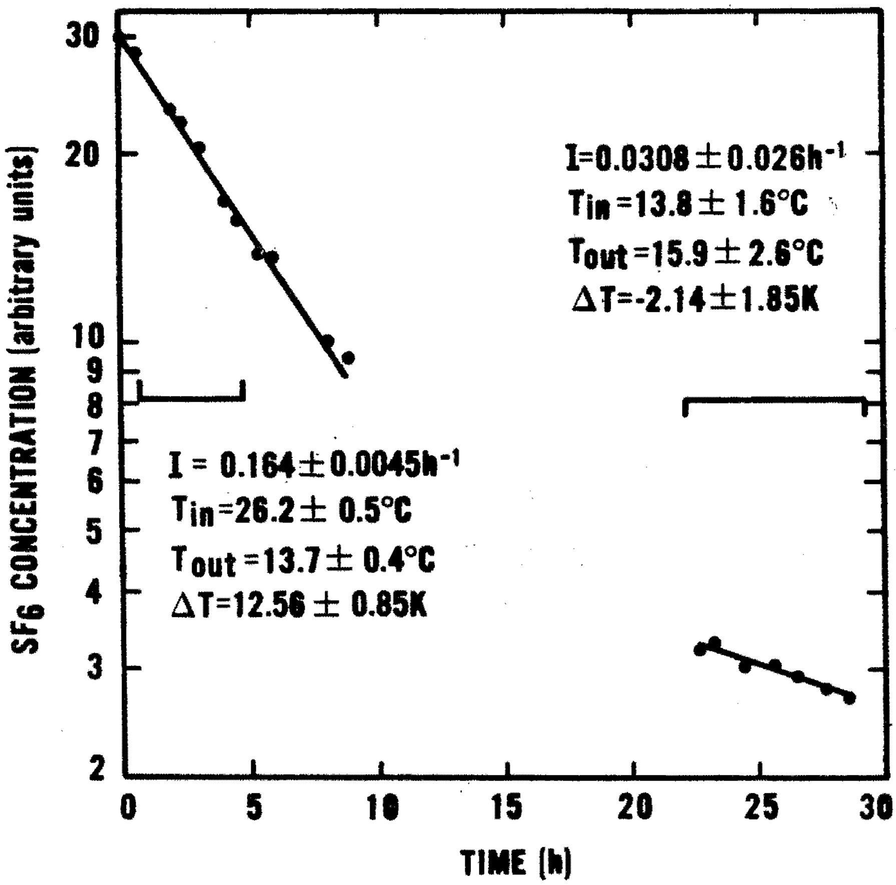

Figure 3. Decay of tracer gas concentration over time. An electric heater in the mobile home was on during the first 3.85 h and the doors between the environmental chamber and outdoor buildings were open until 23.85 h had elapsed. Mobile home-environmental chamber temperature difference remained relatively constant during the time intervals indicated by brackets.

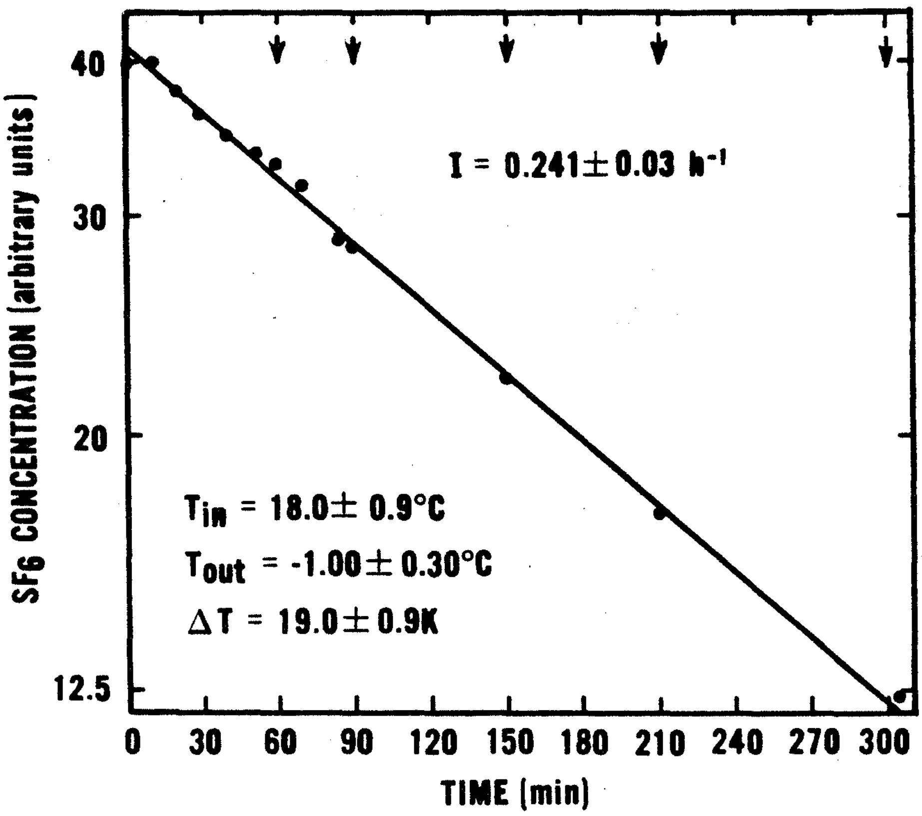

Figure 4. Decay of tracer gas concentration over time at an average indoor-outdoor temperature difference of 19.0 K. Air bags taken in the environmental chamber at the times indicated by arrows showed no SF_6 present.

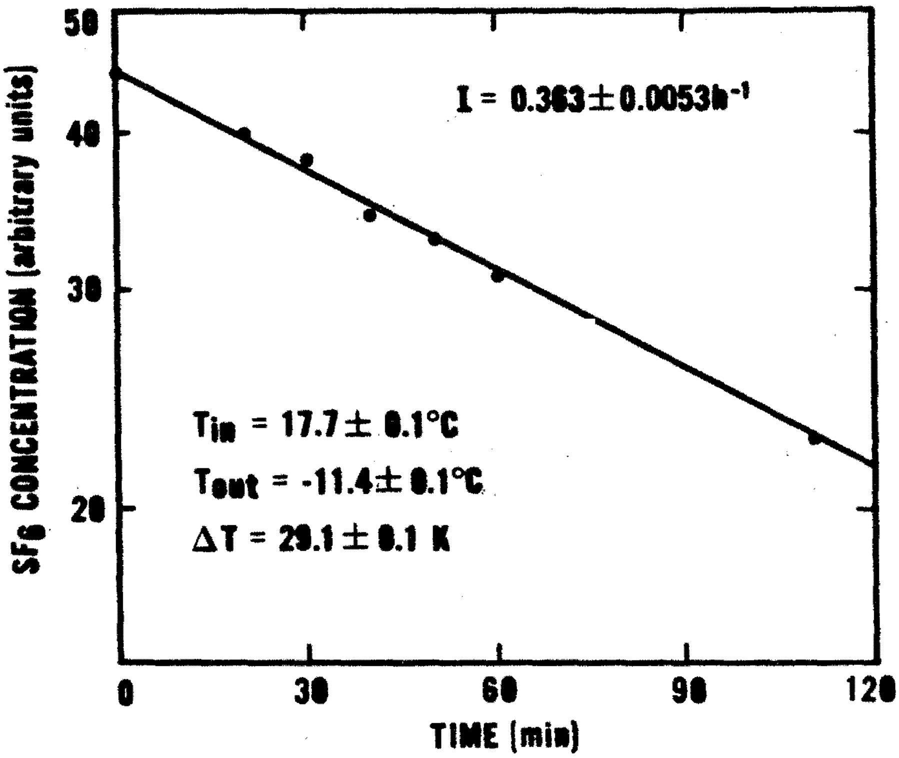

Figure 5. Decay of tracer gas concentration over time at an average indoor-outdoor temperature difference of 29.1 K.

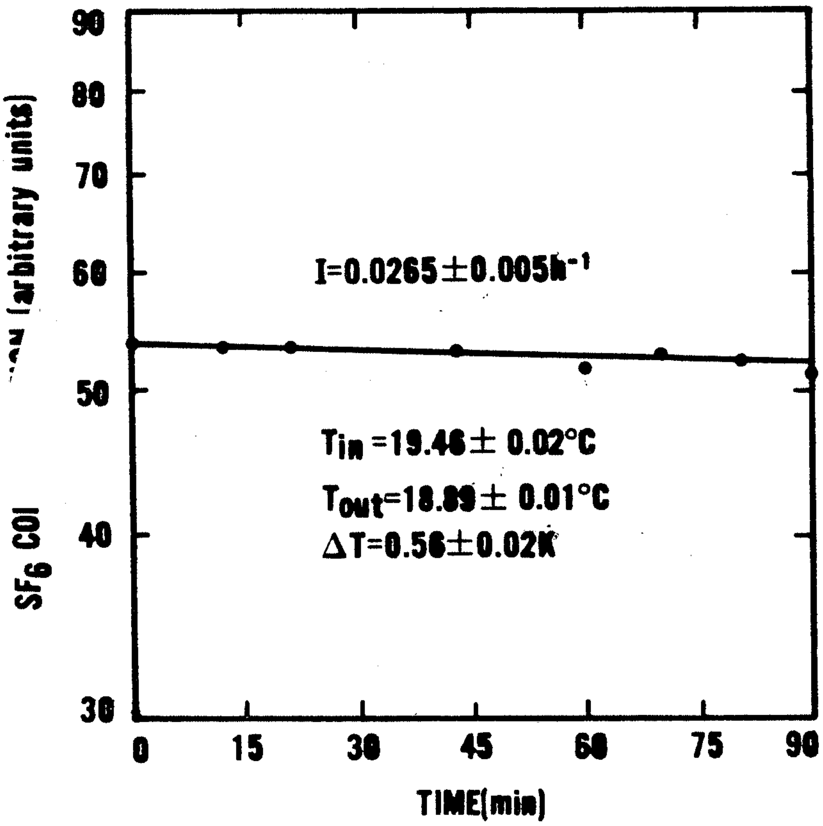

Figure 6. Decay of tracer gas concentration over time at an average indoor-outdoor temperature difference of 0.56 K.

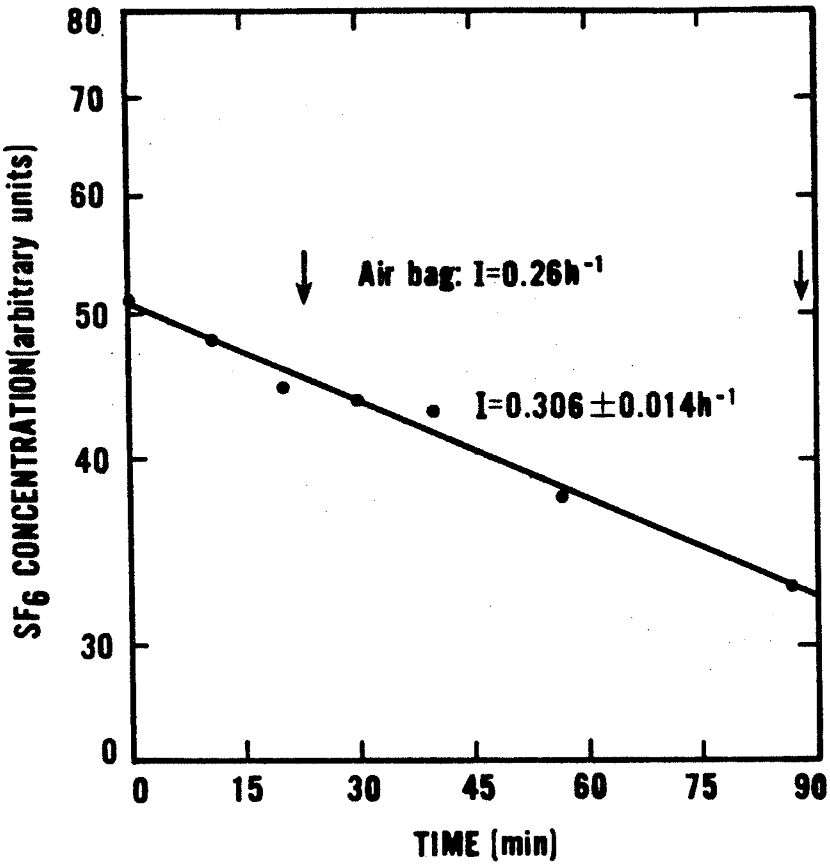

Figure 7. Decay of tracer gas concentration over time with an open window. Air bag samples were taken in the mobile home at the times indicated by arrows.

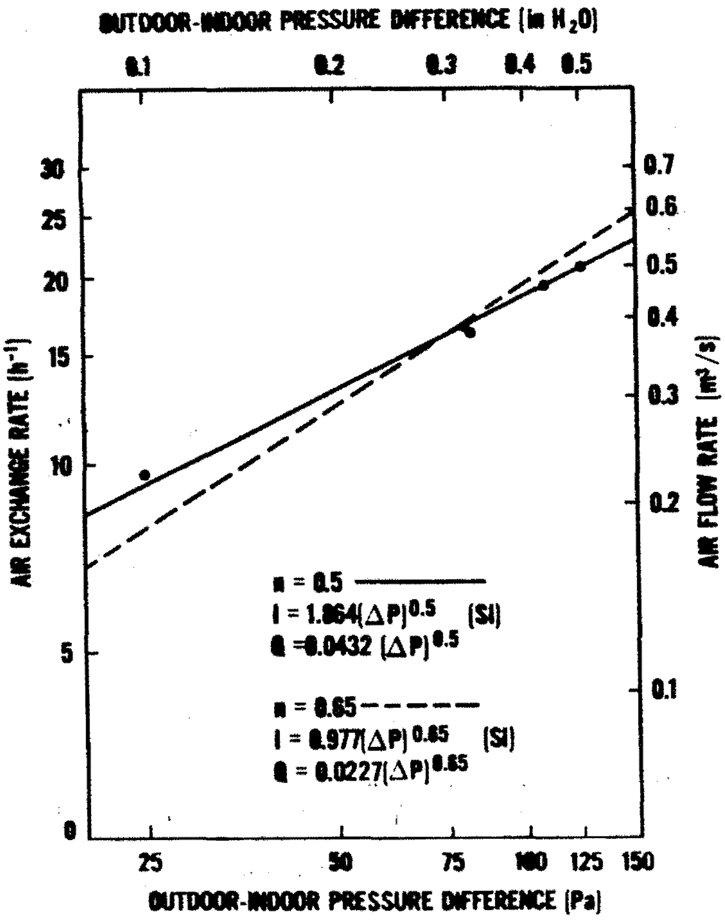

Figure 8. Dependence of air exchange rate on outdoor-indoor pressure difference as measured by fan depressurization. (Data are summarized in Table 3.)

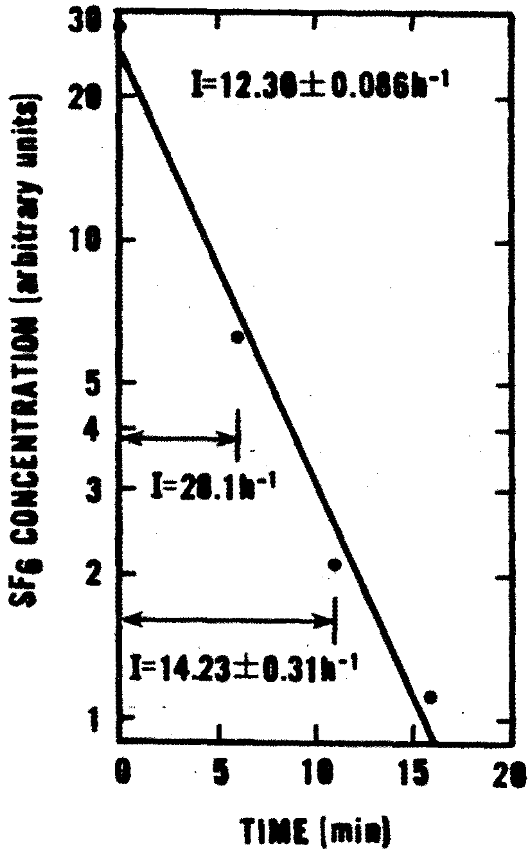

Figure 9. Decay of tracer gas concentration during fan depressurization test.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Air exchange rates, $I(h^{-1})$, of an unpartitioned mobile home were measured at various indoor-outdoor temperature differences, $\Delta T(K)$, using SF_6 tracer in an environmental chamber, and found to be lower than for conventional buildings but similar to other mobile homes. There was little scatter from the regression equation $I = 0.0182 + 0.0118\ |\Delta T|$, with relative standard errors of the first and second coefficients of 62 and 2.5%, respectively.

A fan depressurization experiment was also performed, and yielded a flow coefficient of $C = 1.64 \times 10^{-4}\ m/s{\cdot}Pa^{0.65}$, which is also comparable to that of a previously measured mobile home. It was further found that:
(1) For $I = 0.24\ h^{-1}$, no SF_6 could be detected in the environmental chamber even after five hours, but when $I = 9\ h^{-1}$ for more than five minutes, the tracer gas method could not be used accurately in the environmental chamber even with exhaust fans operating;
(2) The standard error is useful for monitoring whether sufficient concentration measurements were taken at each step;
(3) An air bag sampling technique appeared as good as the conventional monitoring method for determining infiltration rate;
(4) Reported intercepts of regression equations vary greatly from building to building, and it may be difficult to analyze the significance;
(5) The possibility that $I = 0\ h^{-1}$ at $\Delta T = 0$ K cannot be excluded.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Air leakage measurements; environmental chamber; fan depressurization; mobile home; sulfur hexafluoride; tracer gas

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